INSECT PESTS
# of flour mills, grain elevators, and feed mills and their control

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PREFACE

The presence of insects in stored products is one of the main reasons for losses in quality and monetary value. Regardless of how efficiently food crops are managed during storage, processing, and distribution, stored products are vulnerable to contamination by one or more of over 100 insect pests. Therefore, scientific knowledge of stored-product insect pests and safe and effective methods for their control are of concern to everyone responsible for reducing postharvest food loss and maintaining a high quality of stored crops.

Canada is second only to the United States in the volume of wheat exported and we are also a major exporter of barley and oilseeds. Canada's cool, temperate climate not only favors the production of high-quality cereal and oilseed crops, but also keeps the harvested crop relatively free from infestation by most major insect pests of stored grain. Nevertheless, Canadian grains and oilseeds are exposed to such pests when crops are transported internationally.

In striving to keep export grain insect-free and to maintain high standards of sanitation in flour mills, grain elevators, feed mills, and other cereal-processing plants, Agriculture Canada, through its Plant Health and Plant Products Directorate, has established and implemented strict procedures for the inspection of grain elevators, mills, and ships. These inspection programs were initiated during World War II to ensure that the inspected premises met the standards required for handling and processing products free of insects.

Although Canadian plant protection inspectors and other regulatory personnel routinely examine food commodities destined for export markets, they do not have a comprehensive reference book that provides answers to such basic questions as the following: What are the unifying concepts that enable one to understand the grain storage problem as a whole, taking into consideration the differences between insects, mites, and microflora? What kinds of insects are usually associated with stored products in Canadian flour mills, grain elevators, and feed mills? What are the scientific and common names of the insects? What is their frequency of occurrence by city, region, product, season? What is the most effective and safest way of controlling stored-product insects? Which stored-product insects have developed resistance to insecticides? What are the major and minor stored-product insect species of the world and which of these are likely to be a threat in Canada? What is known about the biology, physical limits, and rate of increase of these insect pests?

This book will make available for the first time, under one cover, information on these topics. It should be a valuable reference and training manual for inspectors, pest control operators, mill and grain elevator managers, and graduate students in Canada and for stored-product workers in other parts of the world. Because various insect species that share a stored-product environment have similar requirements, a certain amount of repetition was inevitable in some chapters. This was done to facilitate interpretation of events and to avoid unnecessary cross referencing.

The book is organized into two parts.

Part I (International) is concerned with some basic concepts relating to ecology, morphology, control, and resistance of insects to insecticides. These concepts apply widely and are not restricted to any particular country, environment, or group of insect pests. Detailed information and illustrations of insect morphology and physiology are available in standard textbooks and have therefore not been included in our book. Part I also provides a comprehensive summary of ecological and biological data of almost all major stored-product insect pests of the world.

Part II (Canada) deals with insect problems in Canada's grain storage systems beyond the levels of farm storage and primary elevator. This part is based primarily on a thorough analysis of inspection reports on insects and mites. Such reports were filed over a decade by the plant protection officers of Agriculture Canada who are responsible for issuing phytosanitary certificates for export grain and its products. This part also contains comprehensive accounts of the 10 most common species of insects that occur in the three storage categories covered in this book. Detailed accounts of the khapra beetle, *Trogoderma granarium*, and the European black flour beetle, *Tribolium madens*, are included because of their special quarantine importance to Canada. In a few cases, readers will note differences between Table 1 and Appendix I in the nomenclature of scientific names. This was unavoidable because analysis of data on the computer required that the number of different kinds of insects and mites be maintained at 94, as reported by plant protection officers and listed in Appendix I.

The first two chapters are reproduced with minor modifications from the following papers presented at international meetings by the senior author: Chapter 1 was based on a paper presented at the Symposium international sur la conservation des grains recoltés humides, Paris, France, 3–10 March 1973; Chapter 2 was based on a paper presented at the First International Working Conference of Stored-Product Entomology, Savannah, GA, USA, 7–11 October 1974. We are grateful to the organizers of the symposium (J.L. Multon) and the conference (R. Davis) for their permission to reproduce parts of the papers. Data on the occurrence of resistance of stored-product insects to insecticides (Table 2) are based on the published literature and personal communications with C.E. Dyte and L. Zettler.

Occasionally, biological and ecological data on individual species contained in Chapter 11 may differ from those given in Table 1 because information was obtained from various sources and collected under various experimental conditions.

Some of the fumigants mentioned in Chapter 5 and in subsequent chapters have been suspended from use in Canada since the submission of this manuscript, these being carbon tetrachloride, carbon disulfide, ethylene dichloride, and ethylene dibromide. Furthermore, the suspension of the remaining fumigants is currently under review. Their description in the text has been left intact because a decision on their status is pending. The survey of literature pertaining to information used in this book was completed in June 1983.

We are indebted to the following colleagues for providing assistance in preparing the manuscript and for reviewing portions of it: R.T. Arbogast, A.M. Babey, the late J. Benazet, E. Baker, E.J. Bond, Y. Bousquet, J.H. Brower, C.J. Demianyk, P. Dobie, F. Dunkel, C.E. Dyte, P.K. Harein, G. Hart, R. Hodges, O. Imura, P.T.M. Lum, J.T. Mills, R.B. Mills, D. Ostrowski, A. Schmidt, L.B. Smith, and V. Wright; R. Sims and H. Weiss, for preparing some of the

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Finally, we are most grateful to our wives, Luella Sinha and Dorothy Watters, for their patience and understanding during the preparation of the book.

Part I

International

CHAPTER 1 STORED-GRAIN ECOSYSTEM

Cereal or oilseed crops stored intact or in processed form in grain elevators, flour mills, feed mills, and warehouses become part of an ecological system, or ecosystem. An ecosystem is an arbitrarily created unit in which there is a definite pattern of energy flow and chemical cycling. A small pond or a home aquarium with fish and plants are ecosystems. A proper understanding of the structure and function of such an ecosystem is a prerequisite to developing a long-term strategy for crop storage. Spoilage of harvested crops in a stored-grain ecosystem can be gradual or sudden, implicit or explicit, superficial or devastating, depending on the speed and intensity of interactions among physical, chemical, and biological variables. Major variables are as follows: temperature, moisture, oxygen and carbon dioxide, free fatty acids, location, storage structure, crop species, cultivar and volume, properties of the grain or food, microflora, insects, mites, rodents, and birds. Many variables affect a stored crop, but they seldom act alone or all at once. They interact with the crop, in succession, and in groups among themselves. Generally, the rate of spoilage is slow in the beginning, but as the proper combinations of variables are assembled and maintained and the storage period prolonged, a conspicuous loss of quality occurs in the stored crop. Complex biochemical changes that accompany postharvest maturity of crop kernels such as wheat occur best at a moisture content of less than 14% at 15–45°C and are a critical factor in attaining a high degree of storage stability.

In a stored-grain ecosystem, interactions between the grain and the organisms associated with it begin in the field before the grain is harvested and stored. Because the food energy locked in stored grains (ca. 344 Cal in 100 g of wheat) is a nonrenewable energy reserve within a closed ecosystem, interactions of the grain with abiotic or other biotic agents usually reduce this energy reserve.

For nearly 10 000 years people have been storing grain with a view to using all of it for human consumption and for livestock. Humans need the carbohydrates, fats, proteins, minerals, and vitamins in the grain and do not intentionally share them with other organisms. In reality, however, stored foods are often shared by many organisms other than humans.

There are many ways in which a farmer can lose stored produce. Stored grain, for example, may lose weight, nutritional value (grade, chemical composition, moisture, dockage, and infestation levels), and seed germinability. Moreover, lowering the quality of the grain can seriously damage the reputation of an exporting country in international trade. Most of these losses can be directly and indirectly translated into monetary losses, with considerable socioeconomic and political repercussions.

Although the modern farmer takes various precautions to reduce these losses, such as drying grain and using pesticides, most measures are short-term solutions. Satisfactory control of organisms in stored grain is seldom achieved.

Several abiotic and biotic factors are usually involved in various combinations in the deterioration of stored grain. These include physical and biochemical changes during storage, exposure to extremes of temperature and moisture, growth of microflora, development of insects and mites, feeding by rodents and birds, use of improper structures or containers for storage, and improper management, causing waste and loss of quality.

An explanation for losses in stored grain can be found in socioeconomic realities. Economics, politics, and traditions of a country largely determine type of farming, methods of storing, handling, and transporting, and marketing practices of that country. Because scientists usually have no control over these factors, any long-range technical solution of grain storage problems has to be made within the framework of the socioeconomic realities of the country. From the scientific viewpoint, part of the reason for the continued loss of stored grain in modern societies lies in the myopic and often unidisciplined strategy used to solve grain storage problems. What we urgently need is a reservoir of ecological knowledge on stored grains and their pests that is not limited to national boundaries. Such a reservoir could form the basis for a world-wide strategy for stored-grain preservation.

Storage of grain and other foods generally reflects a dynamic state, although the term *storage* implies an immobile, static state. Cereal grain is a living entity with all the properties of a living organism and therefore cannot be treated as an inanimate object. Although it is alive, the stored seed may not manifest some of its metabolic activities, mainly because it remains in a dormant state in the storage ecosystem. The organisms that attack grain or become associated with it, or with stored food, are also alive and commonly interact during storage. Management of food systems according to long-range goals is effective only when the mechanisms of the decay process are well understood and manipulated.

All stored grains or foods gradually lose quality and decay, even though they are alive or healthy, or both, at the time of initial storage. The aim of proper management of stored food is to slow down or temporarily arrest this process. Decay is a functional characteristic of the stored-grain ecosystem (or the storage ecosystem), not an isolated event involving only one or two biotic and abiotic agents. In the past, most strategies of food storage management have emphasized one or two decay-causing organisms. For example, one group of storage managers has often worked on the bacteriological aspect of food spoilage while ignoring mycological, entomological, or acarological aspects. Depending on the environment, flour beetles can be as important and as relevant as coliform bacteria or *Salmonella*. However, as a food substrate passes from one niche (with a moisture–temperature–time combination) to another, a single group of harmful organisms becomes more important than others that dominated the food scene earlier. The challenge of the storage manager is not to lose the holistic view of the decay process when only one organism is conspicuous in food substrate as it is moved from one phase to another.

To have such a view one must be familiar with some of the concepts and definitions of ecology and use an ecological approach in devising and applying food protection measures. If one does not use such an approach, the results of many of the carefully applied measures could be short-lived, even when they seem to be effective.

Ecology is the systematic study of interactions between plants and animals and their abiotic environment, which determine the distribution and abundance of organisms. In the food industry, these organisms are usually harmful to humans because they lower the quality of food, which can be a living organism itself, as in the case of cereal grains and oilseeds.

An ecologist works with one or more of the following levels of organization: individual, population, community, ecosystem, biome, or biosphere. Energy to sustain life processes flows through all these levels. The most important and the only free energy source available to humans is the radiant energy from the sun. This energy is used in the photosynthetic process of the green plant (the autotroph) whereby carbon dioxide is assimilated into energy-rich carbon compounds. The plant also uses nutrients from the soil's energy and mineral reservoir, which are cycled and recycled as part of biogeochemical cycling. The lowest of these trophic levels is that of the self-nourishing wheat plant, or the true producer of food, and the second level is that of an other-nourishing heterotroph, or consumer, such as a cow or an insect. At each level of transfer, considerable energy is lost through respiration and other metabolic activities. The number of trophic levels can be two, three, four, or five, depending on the extent of stability of the interrelations in an ecosystem. Orderly energy transfer is crucial for survival, propagation, and decay of all living organisms.

The following definitions are useful in developing an ecological approach to food-system management:

population A group of organisms of the same species occupying a particular space at a particular time.

community Groups of coexisting interdependent populations of plants and animals occupying a given place; groups may be of various sizes and exhibit various levels of integration.

ecosystem The biotic community and abiotic environment, e.g., communities of microflora, insects, and mites as they live together and respond to changing temperature and relative humidity of the air. An ecosystem may also be defined as an assembly of interlocking life-systems.

life-system The component of an ecosystem that determines the existence, abundance, and evolution of a population. Such a system has a subject population and its effective environment, which is composed of all external agencies affecting the population. Interlocking life-systems make up the framework of an ecosystem.

In this chapter, we shall be concerned mainly with the community and ecosystem levels of organization. An ecosystem is judged on the basis of its level of maturity, structure, function, and energy flow within it. In an undisturbed ecosystem, maturity increases with time. An ecosystem can be relatively stable and can be designated as the more mature type, with considerable species diversity and food webs containing many interactions, such as are found in coral reefs or tropical rain forests. Stability implies persistence when disturbed and a lack of large fluctuations in population. An ecosystem can also be designated as the less mature type if it has a simple food web, a low species diversity, and only a few successional changes, such as abundant agricultural lands. An individual species lacks a high degree of specialization and many of its populations succumb to abiotic population control forces. Although populations can rebuild their numbers quickly, climatic stress and outside interference can prevent communities within such ecosystems from progressing toward a higher level of maturity.

Succession of species population and energy flow play an important part in ecosystem development. Succession allows undisturbed ecosystem communities to develop high species diversity and greater homeostasis and stability, thereby providing protection from environmental disturbance. The maturity concept, in terms of species succession and energy flow, provides an excellent working hypothesis to explain the structure and function of an ecosystem constructed by humans, such as postharvest grain.

Food web (structure) and energy flow of a stored-grain ecosystem

To understand the ecology of storage, one should consider a grain bulk as an ecological system in which the abiotic physiochemical environment and the biotic assemblage of flora and fauna interact with each other (Fig. 1). A grain bulk is an immature ecosystem made by humans, with a relatively simple structure and a nonregenerating food supply. Energy captured by the cereal plant producers is concentrated in stored seeds and is used to maintain the simple ecosystem. Because of frequent interference from the physical environment and from humans, such an ecosystem is unstable. Only species with high growth and reproductive rates and low specialization seem to do well in this type of ecosystem. The concentration of energy per unit of biomass is relatively high. Unlike mature and stable natural ecosystems, such as tropical forests or prairie grasslands, patterns of relationships among biotic elements and between biotic and abiotic elements are vague and often too transitory to quantify and define. And yet because of the valuable resources they represent, ecosystems made by humans are important to people. Only by understanding the functional dynamics of these ecosystems, can we hope to develop management practices and exploit fully the resources of the ecosystems.

The pattern of energy flow in grain-bulk ecosystems—that is, the transfer of food energy in a food chain from the plant seeds through food webs to higher trophic levels conforms to fundamental thermodynamic principles: energy is neither created nor destroyed, but it can be transformed; in real processes energy cannot be quantitatively converted into another state without some loss of energy in a randomized and dissipated form. At each of two to five transfers or trophic levels in an ecosystem, a large proportion of the potential energy is lost as heat. As a result of oxidation processes that liberate carbon dioxide, heat is generated whenever an organism respires. For example, a 2-day culture of fungal mold liberates carbon dioxide at a rate of 1750–1870 mg/g of dry matter in 24 hours, whereas the respiration intensity of a dry wheat kernel in the same period is less than 0.1 mg. Grain weevils are estimated to liberate 130 000 times more carbon dioxide than the equivalent weight of grain. Food webs created by interlocking food chains in an aging, stored grain bulk are illustrated in Fig. 1. Only a few major representative organisms are shown. First-level consumers include the following: the fungal genera *Aspergillus* and *Penicillium*, actinomycetes, and bacteria, all of which not only feed on grain but also produce toxic substances; granivorous beetles, such as *Sitophilus*, *Rhyzopertha*, *Trogoderma*, *Oryzaephilus*, *Tribolium*, and *Cryptolestes*; moths, such as *Sitotroga*, *Ephestia*, and *Plodia*; acarid and glycyphagid mites; rodents, such as rats (*Rattus*) and mice (*Mus*); and birds, such as sparrows and pigeons.

The microbial consumers (decomposers) can flourish and decompose organic matter successfully only when the food source has a carbon-to-nitrogen ratio that ranges from 15:1 to 30:1. Most cereals have a carbon-to-nitrogen ratio within the optimum range of microbial activity (wheat, 15:1–26:1; barley, 18:1; oats, 20:1; and rice, 25:1).

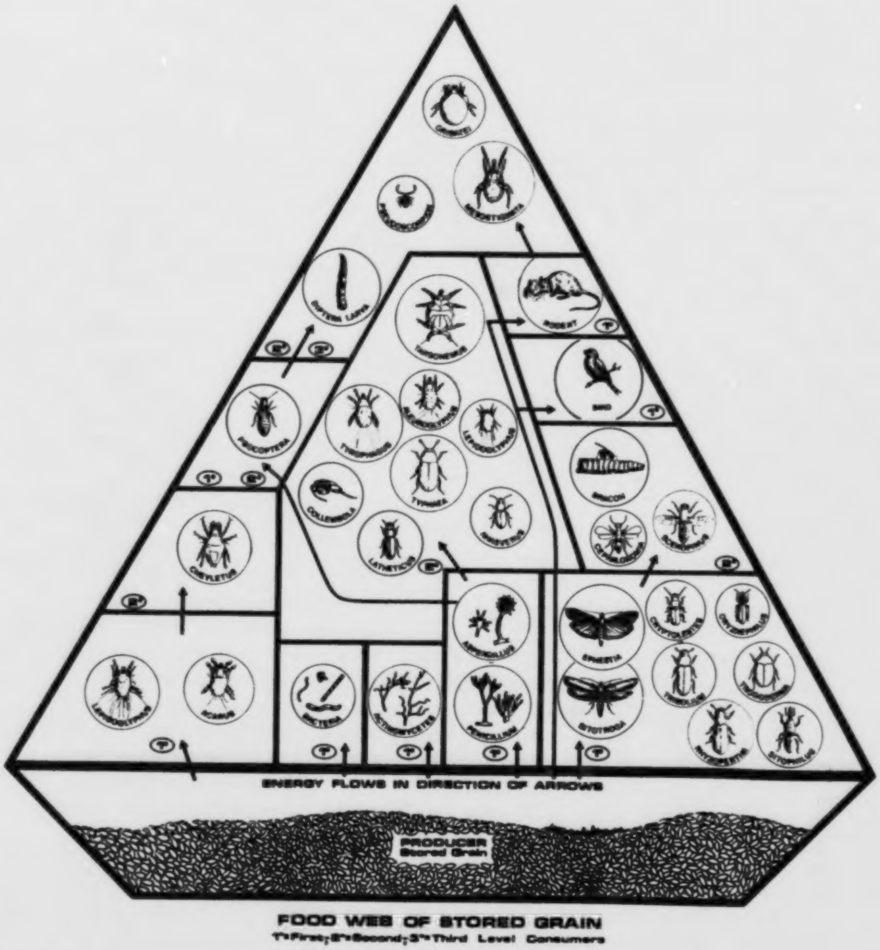


Fig. 1 A schema of a food web showing various plant and animal forms that are associated with stored grain and its products; the arrows indicate the direction of energy flow and the numbers, the trophic levels.

However suitable the substrate may be, most microorganisms (except some species of *Aspergillus*) are inactive unless the moisture content of the grain is high (70%+ relative humidity for most fungi and actinomycetes, and 90%+ relative humidity for most bacteria). Moreover, fungal infection is facilitated by seed injury. The first-level consumer insects injure the grain and thereby provide routes of entry for various microflora and other secondary insects and mites. In addition, the nitrogenous waste products and metabolic moisture from insects provide more favorable carbon-to-nitrogen ratios and moisture levels, thereby facilitating further microbial infection. Rodents and birds, as first-level consumers, not only consume a sizable quantity of the grain but also foul a larger quantity with their excrement, hairs, and feathers. Most mites and psocids feed on grain debris and the fungi that grow on the grain. But *Acarus siro*, which feeds directly on wheat germs and multiplies to large numbers, is more a first- than a second-level consumer.

The first-level consumers in turn produce food for the second-level consumers. The latter include insectivorous birds and rodents, mycophagous insects (*Ahasverus*, *Latheticus*, *Typhaea*), and mycophagous mites (*Tarsonemus*, *Caloglyphus*, *Tyrophagus*, *Aleuroglyphus*), all of which feed on the fungi that invade the grain. Also at the second level are mite and insect predators and parasites, such as *Cheyletus* and *Spinibdella*, which feed on acarid mites; parasitic wasps, such as *Bracon* and *Cephalonomia*, which feed on larvae of stored-grain moths and beetles; and *Blattisocius* mites, which feed on *Ephestia*. Third-level consumers include dipterous maggots, which are parasitic on rodents and birds; pseudoscorpions; and tydeid and mesostigmatid mites. Because the feeding habits of many insects and mites are still unknown, third-level consumers are sometimes difficult to separate from second-level consumers. Excrement from the primary consumers, which is the site for luxuriant microbial growth, is also eaten by certain secondary and tertiary consumers (scavengers). Other nutrients for decomposer microflora are provided by the dead bodies of various animals. Recycling of nitrogen and other essential food components from one organism to another continues. Such recycling of nutrients gradually makes the grain bulk unsuitable for human use.

Role of communities of insects and microflora in an ecosystem

The role of insects can be better understood if the insects are examined as part of an entomological community. Community ecology includes the study of the structure (species composition, diversity) and the succession of species or species groups, and competition (interspecific and intraspecific).

Various insects that can attack relatively dry stored grain and foods (above 10% moisture content) at 15–42°C in all parts of the world constitute one of the most successful biotic communities in the storage ecosystem. Having originated in the tropical or subtropical parts of the world, most storage insects do not hibernate. They persist in cooler parts of the world only by finding and creating a favorable environment, either within bulk food or in a food store. Interrelations among biotic and abiotic variables in the animal (insect) and plant (microflora) communities in insect-infested ecosystems can be shown from the case study that follows.

The impact of insect infestation on certain biotic and abiotic variables of 10 wheat bulk ecosystems exposed to the extreme climates of the Canadian prairie was studied by measuring these variables monthly during 1969 and 1970. In addition to an insect-free ecosystem (control), one set of ecosystems was artificially infested with *Cryptolestes ferrugineus* and *Oryzaephilus surinamensis* and the other set with *Sitophilus granarius* and *Tribolium castaneum*. Changes in temperature, moisture, viability of the grain, grain weight, dust weight, species of microorganisms and insects, fat acidity value, and uric acid content were measured monthly and analyzed separately by conventional descriptive and multivariate statistical methods (principal component analyses). The analyses gave a clear picture of the pathways of biological and chemical deterioration of the grain in the systems. In the control system, the fungus *Alternaria alternata* decreased, and *Aspergillus versicolor* and *Penicillium* spp. increased, probably causing a moderate rise in the fat acidity of the grain and a slight drop in the grain weight. In the second system, *Cryptolestes* and *Oryzaephilus* attacked few sound kernels, but polluted the environment with excreta and remains, and appeared to accelerate the deteriorative processes observed in the control system. In the third ecosystem *Sitophilus* and *Tribolium* thrived, involving the creation of large amounts of frass, the invasion of *Streptomyces* and bacteria, and the further acceleration of deteriorative processes.

This study showed that time and the physical environment (especially temperature) dominated both the insect-free and the insect-infested systems, particularly the one infested with *Cryptolestes* and *Oryzaephilus*, which was only slightly influenced by changes in microflora and free fatty acid levels. These insects, however, were able to pollute the wheat by excreting uric acid. The system infested with *Sitophilus* and *Tribolium* was affected by metabolic moisture created by the insects. The addition of this moisture to the system accelerated the development of *Aspergillus*, *Penicillium*, *Streptomyces*, and bacterial populations. The main conclusion from this ecosystem analysis is that within a favorable range of moisture conditions, temperature sets the limits for survival and multiplication of stored-product insects in Canada's Prairie Provinces.

Finally, three main characteristics of insect species that invade food storage systems help one to understand the infestation process: the ability to accommodate to changing human societies, cultures, and civilization; the ability to multiply quickly; and the capacity to use a wide range of natural and processed foods. When these characteristics, which are shared by all biotic agents, are considered against the background of living bulk grain or nonliving processed food, the various aspects of the food-loss problem can be better understood and a workable holistic, long-term strategy for the safe storage of grain can be developed.

The ecosystem approach for pest management and safe food storage

The concepts of modern ecology as applied to grain storage problems can be used profitably to prevent and control insect infestation and improve management of stored foods in flour mills, grain elevators, and feed mills. By using the ecosystem approach, a storage manager can routinely monitor information about several variables that might contribute to deterioration and loss of quality in stored food from the beginning of storage to the time of its removal, sale, or consumption. The variables affecting the stored food ecosystem may include the following: intergranular air composition (carbon dioxide and oxygen), water vapor, dockage, grain viability, rodents, insects, fungi, actinomycetes, bacteria, and granary structure. As the variables are monitored, both their individual roles and interactions can be evaluated in terms of their potential for food loss or preservation. This type of information enables the manager to decide on the timing, which is the most important variable to be tackled, and the preventive or control measures to be applied so that reduction in quality and economic loss of the stored food are minimized. Ideally, this type of information can be fed through a computer to predict a safe storage time. Several quality-loss situations can be simulated, and solutions for prevention and control can be suggested. Thus, a safe storage period for moist wheat stored in an elevator bin can be predicted throughout the storage period if specific data on storage structure, temperature (outdoor and intergranular), moisture content of the grain, and type of pest are known.

CHAPTER 2 INFLUENCE OF CLIMATE ON STORED-PRODUCT INSECTS AND AN INDEX OF THEIR ADAPTABILITY

Plant and animal pests that infest foodstuffs operate within specific limits imposed on them by their genotype, climate, and geographical distribution. The causes and consequences of infestation of foodstuffs are complex; cereal grains and the organisms that attack them not only have characteristic properties but they also are affected by many physical, chemical, biotic, and external variables. For example, a crop of Manitoba wheat may be harvested damp by a combine, infected by fungi and bacteria, dried by a drier, stored in a metal bin, subsequently infested by insects, fumigated, and transported by a truck, a railway boxcar, and a ship.

Climate is defined as the mean physical conditions that have a major effect on the mean population density of a species. Weather is defined as day-to-day or seasonal conditions that have a major influence on the survival of organisms. For convenience, weather is considered as a component of climate in this publication. Climate changes the quality of stored grain by influencing harvest, storage conditions, and rate of increase of various biotic agents that invade stored grain (Fig. 2).

In this chapter, we are primarily interested in the role of insects in effecting change. Therefore, Fig. 3 shows how climate, insect genotype, and nutrition can lead to insect outbreaks, spoilage of stored cereals, and economic loss. Indirect effects of climate on insect populations act through endocrine systems, parasites, predators, microflora, and structural and other types of barriers as shown in Fig. 4. Weather affects insects by acting on the endocrine system, which regulates diapause initiation and influences survival, development, and reproduction; weather also affects the individuals of a species as a density-independent catastrophic factor. Because many stored-product insects live in a relatively protected environment provided by a mass of foodstuffs around them and only a few species (e.g., *Sitotroga cerealella*) undergo diapause, the effect of weather is often not conspicuous. Diurnal, seasonal, and annual changes in temperature and relative humidity, particularly where such changes are pronounced can, however, critically determine the population size of a stored-product species. In a stored-grain environment, insect performance can also be affected by the growth of fungi, bacteria, parasites, and predators, which in turn are influenced by climate. In addition, the genotype of a species and the nutrition provided by the stored seeds also influence the three basic physiological processes of the insect. If an insect species can exploit the climatic and other conditions of its environment to its advantage, it will succeed and multiply explosively to outbreak numbers. At this stage, human action or weather, or both, may prevent the insect population from flourishing further. If control measures are applied, insects cease to thrive and the stored grain is salvaged for human or animal use. If no control measure is applied, cereals can be totally spoiled, causing eventual death of the insects by starvation, exposure, and toxic substances produced by their own bodies and by microbial species.

To explain clearly the climatic effect on insect infestation and spoilage of stored cereals, only environments, cereal types, and insect species of certain categories are considered in this publication.

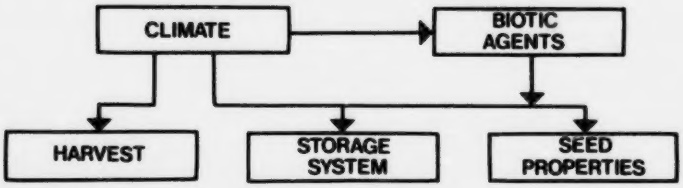


Fig. 2 A schema illustrating the general influence of climate on cereal harvest, storage system, seed properties, and biotic agents that infest stored cereals.

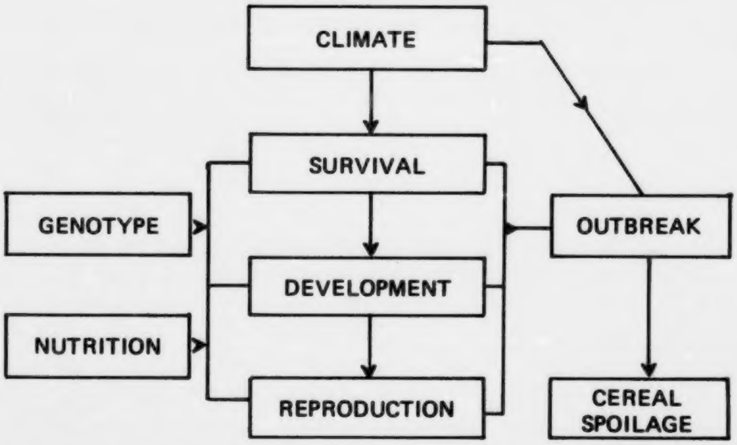


Fig. 3 A schema of the main effects of climate, genotype, and nutrition on a stored-product insect population that lead to an insect outbreak, cereal spoilage, and economic loss. Climate also includes weather effect.

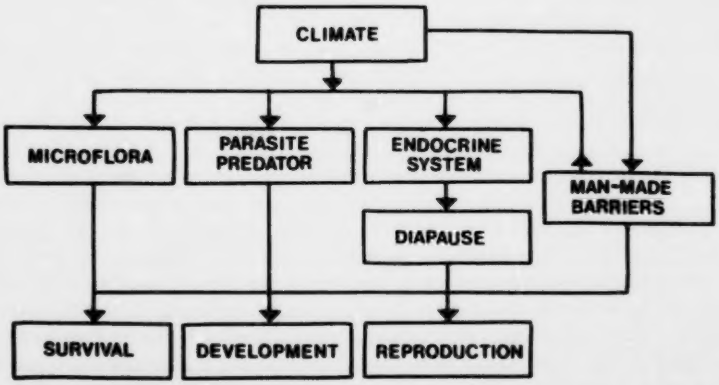


Fig. 4 A schema of the indirect effect of climate on insect population through its own endocrine system, parasites and predators, seed-borne microflora, and man-made structural barriers.

Environment

The habitats of stored-grain insects are broadly divided into two types of environments, unprotected and protected.

In an unprotected environment, there is minimum protection from climate, although temporary insulation is provided by the structure and the cereal substrate. Insects can be found in empty or small granaries, bags, metal bins, and earthenware containers.

In a protected environment, there is adequate protection from climate and weather, e.g., large grain bulks; large, well-constructed grain elevators and silos; and heated, refrigerated, or air-conditioned granaries, warehouses, and flour and feed mills.

The effect of climate described in this chapter covers both unprotected and moderately protected environments. The latter include buildings without heating or cooling systems.

Cereal crops

Insect infestation of only major cereal types is considered. The cereal crops include wheat, rice, corn (maize), barley, oats, sorghum, millet, and rye.

Insect species

Pests are arbitrarily assigned to one of four categories, designated for use in this chapter only. Principal pests are destructive and occur in large numbers, usually throughout the year. They usually attack at least one major cereal, and usually less than five species occur in a country. Major pests are destructive, occasionally breaking out in certain types of cereals at certain times of the year. Usually, less than 10 species occur in a country. Secondary pests can be common or occasional, and are economically less important than principal and major pests. More than 100 species may be found in a country. Associated insects can be incidental or sometimes common and are of questionable economic importance.

Only principal and major pests are considered in this bioclimatic analysis. All species referred to as insects or pests in the pages that follow are stored-product insect species. Today's highly developed global transport system allows frequent exchanges of large volumes of stored foods between various countries in several climatic zones of the world. Despite national quarantine and food inspection safeguards imposed by individual countries, some pests accompany foodstuffs and are accidentally introduced as new pests in certain countries. Even in countries such as Britain and Japan, in which insect quarantine laws are enforced and records are kept, new pest species have been reported at one time or another. Often, the geographical range of a single species, or of a combination of stored-product species, is restricted to one or two climatic zones. There are two reasons for such distribution: the food commodity is restricted, e.g., absence of *Corcyra cephalonica* in temperate wheat-producing countries, and the weather conditions in surrounding climatic zones are unsuitable for its survival. The species composition of well-established insect fauna, however, often reflects the climatic condition of a region during a certain period. Although climate provides the basic physical environment of the habitats in which insects can flourish, it does not account for all the causes of an insect infestation; the causes and consequences of insect infestation are almost always related to grain harvesting, drying, moisture content, microflora, rodents, design of granary structures, and duration of storage. Nevertheless, because most of these variables are also affected by climate, the role of climate is crucial in explaining many combinations of principal or major pest species in a country or a group of countries.

To understand how climate affects the ability of stored-product insects to succeed or fail as pests, one must first consider the behavior of two crucial climatic variables, temperature and moisture (affected by relative humidity), and then examine the relationship between atmosphere and water in relation to the biotic characteristics of the insect species and the food they infest.

Temperature

Temperature is a regulating factor in the survival, development, and reproduction of all organisms, and its effect is correlated with the amount of water present in the atmospheric air. High temperature accelerates the life processes of all organisms. Generally, stored-product insects develop progressively faster from 20 to 35°C, and die within 5–7 degrees above this range. Thermal death points at low temperatures are more variable.

Moisture

All organisms require water to survive and multiply. The exact quantity of water or the absolute moisture content, expressed as grams of water vapor per cubic metre of air in atmospheric air, determines the level of biotic activity of an organism. The water-carrying capacity of air, as expressed by relative humidity, increases with a rise in temperature. For example, at 10°C air can hold water at 10 g/m^3; at 38°C, 45 g/m^3 (Fig. 5). Because at 38°C air that contains 10 g of water holds only 22% (10/45 = 22%) of the amount of water that it could hold at the saturation point, air shows a strong tendency to absorb water from the biotic materials it surrounds. This process deprives the organism of the vital water supply and retards its biotic activity. As the atmosphere cools to 32°C (water retaining the initial rate of 10 g/m^3) the air requires water at only 33 g/m^3 to reach saturation (10/33 = 30% of saturation point); correspondingly, its tendency to acquire water is reduced, thereby increasing the availability of water to other material. In an atmosphere of constant absolute water content, the relative humidity of the air decreases with an increase in temperature (Fig. 6).

Classes of climatic zones

In 1900, Wladimir Köppen developed a system of classifying climatic regions of the world based on five temperature limits, or belts. Although his system has been modified with changed boundaries and is more sophisticated today, it is still

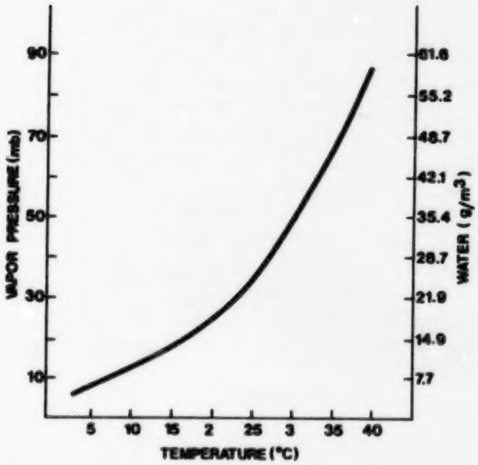


Fig. 5 Water- and vapor-pressure saturation levels in atmospheric air at various temperatures. The carrying capacity of an absolute quantity of moisture by the atmospheric air increases with rising temperature, resulting in a greater demand by the air for moisture from free water and from within organisms.

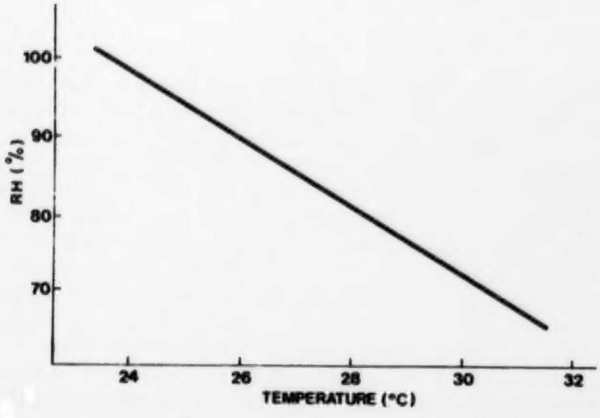


Fig. 6 Linear relationship between relative humidity (RH) and temperature in an atmosphere containing a constant water content (21.7 g/m^3).

the basis of all global climatic classifications and is one of the oldest in existence.

These regions are as follows: tropical belt, 12 months above 20°C; subtropical belt, 4–11 months above 20°C, 1–8 months from 10 to 20°C; temperate belt, 4–12 months from 10 to 20°C; cold belt, 1–4 months from 10 to 20°C, 8–11 months below 10°C; and polar belts, 12 months below 5°C.

Most major stored-product insects do not multiply well enough to be pests below 20°C and they therefore cannot infest stored products in cold and polar belts. They thrive and multiply best in the tropical belt and, to a lesser extent, in the subtropical and temperate belts. Most cereals of the world, however, are neither produced nor stored for long periods in the tropical belt. Humid middle-latitude prairie grasslands, which constitute 7% of the land area of the earth and in which about two-fifths of the world's population lives, produce the most cereals including wheat, barley, oats, corn, and rye. Fortunately, home-grown stored cereals in this region are not often subjected to year-round heavy insect infestations similar to those common in the humid tropical belt. Stored products are infested by cosmopolitan insect species in climates that are similar to those of the farmlands of the world. See Fig. 7 for a modern climate classification of agricultural lands of the world.

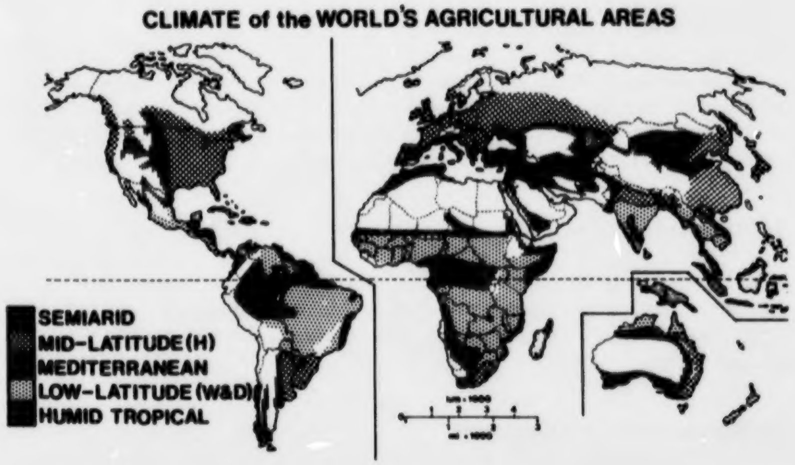


Fig. 7 Climatic areas of the world's farmlands.

Crop-producing areas and storage areas classified by climate

Semiarid lands

Summers are hot, as are winters in low latitudes; winters in middle latitudes are cool to cold. In dry seasons there is less than 38 cm of rainfall. Typical countries include Egypt, Sudan, Niger, Somali Democratic Republic, and Pakistan. Major cereal crops are millet and sorghum. The land often requires irrigation. *Lasioderma serricorne*, *Trogoderma granarium*, *Tribolium castaneum*, and *Sitotroga cerealella* are typical major storage insects.

Low-latitude wet-and-dry lands

All seasons are warm or hot. The wet season is preceded by a dry season, and the weather is slightly cooler in the low-sun period of the year. Typical countries include India, Thailand, Brazil, Ghana, Burma, Sri Lanka, and Indonesia. Major cereal crops are rice, corn, and other cereals. *Sitophilus oryzae*, *Rhyzopertha dominica*, and *Corcyra cephalonica* are typical major storage insects.

Mediterranean lands

The climate is warm to hot year round, with dry summers and cool to mild humid winters. Typical countries include Italy, Greece, Turkey, Israel, and Portugal. Major cereal crops are corn, barley, and oats. *Ephestia cautella* and *Sitophilus granarius* are typical major storage insects.

Humid tropical lands

The climate is hot and moist year round. Typical countries include the Congo, Colombia, Venezuela, Burma, and Indonesia. Major cereal crops are rice and corn. *Sitophilus zeamais*, *Sitophilus oryzae*, and *Sitotroga cerealella* are typical major storage insects.

Middle-latitude humid lands

The climate includes four distinct seasons, with warm to hot summers and cool to cold winters. The frost-free period is more than 90 days long, varying with latitude; it is humid most of the year. Typical countries include northern United States, USSR, China, Australia, western Europe, Canada, and Japan. Major cereal crops are wheat, barley, corn, and all other cereals except tropical crops. *Sitophilus granarius*, *Oryzaephilus surinamensis*, and *Tribolium* spp. are typical major storage insects.

This group has four subdivisions: humid continental with short summers (major cereal crops: spring wheat, barley, and oats; typical major storage insects: *Cryptolestes ferrugineus* and *O. surinamensis*); humid continental with long summers (major cereal crops: corn and winter wheat; typical major storage insects: *S. oryzae*, *Tenebroides mauritanicus*, and *Tribolium castaneum*); humid subtropical (major cereal crops: wheat and rice; typical major storage insects: *O. surinamensis* and *S. granarius*); and West Coast marine (major cereal crops: wheat and rice; typical major storage insect: *O. surinamensis*).

Climatic effect at various levels of storage

Climate affects stored cereals and their insect pests at every stage during storage and transportation. The degree of climatic effect depends primarily on the extent of protection provided by the design of granary structures, trucks, railway cars, ships' holds, and the size of bulks or bags. Fig. 8 illustrates a schema of levels of storage in Africa and Fig. 9, in North America. Climatic effect is usually most severe at lower elevations.

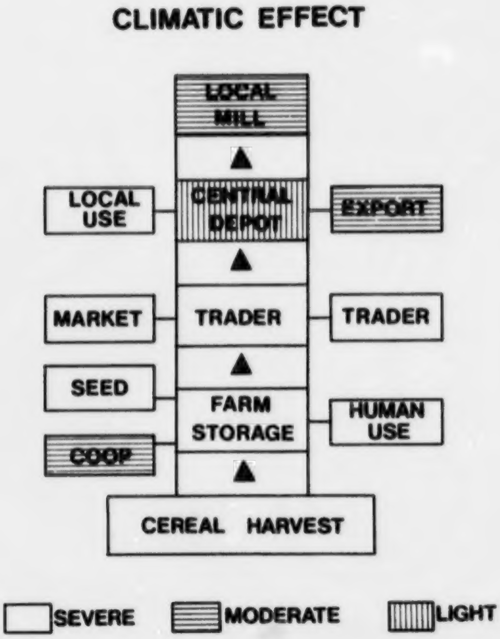


Fig. 8 A schema showing the climatic effect on stored cereals and their pests at various stages of the grain storage, transportation, and processing system in developing countries in Africa and elsewhere.

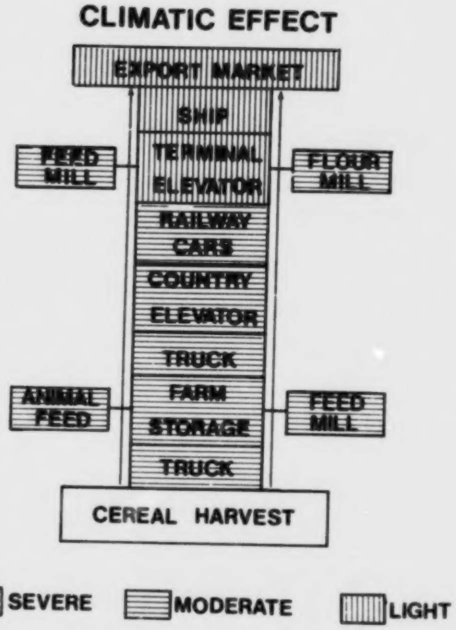


Fig. 9 A schema showing the climatic effect on stored cereals and their pests at various stages of the storage, transportation, and processing system in North America and other industrialized, midlatitude, humid countries.

Climatic plasticity index—a measure of insect adaptability

Whether a stored-product species causes economic loss in a climatic zone in which there is adequate suitable food depends on the physical limits and on the optimum range of temperature and relative humidity within which the species can multiply. Although several major insect species occur in most food-producing and populated parts of the world, some species are particularly destructive in certain climatic zones but are scarcely present in others. To cause outbreaks in any climatic zone, a species must be able to reproduce quickly in favorable periods of the year and survive with a sizable residual population during unfavorable periods. Laboratory life history studies of 51 species of stored-product insects show that their rate of increase is optimized within a narrow 3–4°C temperature range, usually at 60% relative humidity or higher. Most species do not reproduce fast enough to cause problems until temperature is about 3–5°C above the laboratory minimum and the maximum temperature at which they will multiply is about 4°C above the optimum.

The reasons for the present distribution, and clues for potential range of distribution of the storage species in relatively unprotected environments, can be found in the inherent ability of a species to adapt, multiply, and build large populations in an area. By integrating the laboratory data (see References) on the biology of each of 51 species, a plasticity index statistic (I_p) can be developed to describe the potential ability of a species to adapt in various climatic zones. The higher the I_p value, the greater the climatic adaptability of the species.

Calculation of plasticity index

For a given species, assume that the function that relates ambient temperature (E) to the rate of increase is known. Then the integral of the function represents an average reproductive potential for all temperatures and could be considered an index of plasticity of the species.

$$I_t = \Sigma\lambda\,(t)dt \qquad (1)$$

I_t is the index of temperature assuming equal weight to every temperature.

The figure could be made more precise for a particular climatic zone by integrating with respect to actual temperature distribution. If F_c is the probability distribution of temperature for a given climate c, we could calculate:

$$I_{tc} = \Sigma\lambda\,(t)dF_c(t) \qquad (2)$$

If λ for a species is not known at all temperatures, we can approximate it.

The parameters as given by the British scientist Robert Howe are as follows:

t_0 = minimum temperature for reproduction
t_1 = lowest limit of optimal range
t_2 = highest limit of optimal range
t_3 = the highest limit of reproduction is assumed as $t_2 + 4$°C.
λ = the rate of increase for a lunar month; that is the maximum rate at which a population with a stable age distribution can multiply, given unlimited food supply.

The function is approximated by the trapizoid (Fig. 10). I_t is then the area between t_1 and t_2.

$$\text{Hence } I_t = \frac{\lambda}{2}\,(t_3 - t_0 + t_2 - t_1) \qquad (3)$$

To make the model more realistic we also include the effect of relative humidity on this insect.

If h_0 is the minimum relative humidity and
h_1 is the maximum relative humidity

$$\text{Then } I_h = (h_1 - h_0 - 5) \qquad (4)$$

Five is subtracted to account for the reduction in reproduction as the relative humidity decreases to its minimum level.

When items (3) and (4) are combined, the plasticity index is

$$I_p = \frac{\lambda}{2}(t_3 - t_0 + t_2 - t_1)\,(h_1 - h_0 - 5). \qquad (5)$$

The actual data for computation were taken from the published information cited from various sources (see References). When a group of species is considered

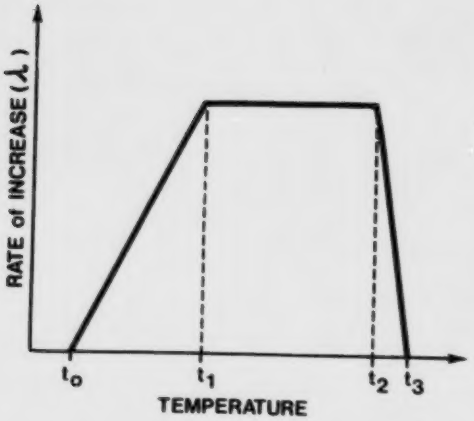


Fig. 10 A schema illustrating how a climatic plasticity index of a stored-product insect species can be calculated. Ordinate = rate of natural increase per lunar month. Abscissa: temperature, t_0 = minimum temperature for reproduction; t_1 = lowest limit of optimum range; t_2 = highest limit of optimum range; and t_3 = highest limit of reproduction incorporating Robert Howe's assumption at t_2 + 4°C. The central area indicates optimum multiplication of the species.

tolerant of low relative humidity, 80% relative humidity is used in the equation; similarly, for other species groups that need moderate and high relative humidity, 90 and 100% relative humidity figures, respectively, were used.

A ranking of 51 species on the basis of their I_p values is given in Table 1. The species that have some of the highest I_p values—*Tribolium castaneum* ($I_p = 588$) and *T. confusum* ($I_p = 478$)—are in fact the most cosmopolitan pests of stored cereals and other foods. By contrast, the rice moth *Corcyra cephalonica*, which is a specialized but dominant pest of rice only in low-latitude wet-and-dry lands, has an I_p value of only 110. *Trogoderma granarium*, which is restricted to a hot and dry climate, also has a low I_p value of 131. Some of the most destructive stored-product species, such as *Rhyzopertha dominica* ($I_p = 190$), are not necessarily the most flexible species with regard to their ability to flourish in various climatic zones of the world.

Climate and cereal infestation patterns

Africa (humid tropical, semiarid, low-latitude wet-and-dry, and Mediterranean)

Africa has a wide variety of climates, which provide four combinations of climatic conditions: hot–damp, hot–dry, cool–damp, and cool–moist–dry. Hot–damp conditions cause the most serious storage problems and cool–dry, the least. Harvesting of the main cereal crops—corn, rice, sorghum, and millet—occurs almost every month of the year, depending upon the crop and the region. In Nigeria, corn is harvested in July and August and rice from October to January. Hot and damp conditions and other local climatic and agricultural characteristics have allowed two insect species, *Mussidia nigrivenella* (Ragonot) and *Cathartus quadricollis* (Guérin-Méneville), to predominate as pests of corn in Ghana, Togo, and Nigeria (Fig. 11). The voracious phycitid moth larvae *M. nigrivenella*, which attack mature but undried grains, often cuts deep grooves through the length of the corn cobs and consumes or damages as many as 20 grain kernels. Larvae of *C. quadricollis* invade uninjured grain at 30% moisture content but later confine themselves to damaged grain. The major storage-insect species groups for selected countries of Africa are given in Fig. 11.

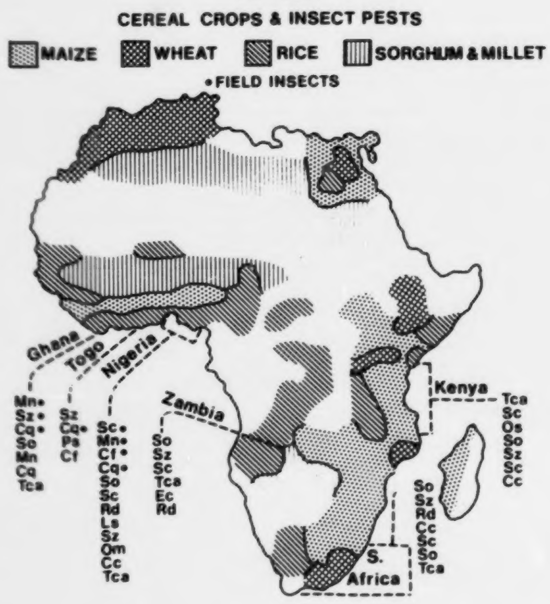


Fig. 11 A map of Africa showing major cereal crop zones and major stored-product insect species that infest cereals in fields and in storage in selected countries. The abbreviations for species names are as follows: Mn, *Mussidia nigrivenella* (Ragonot); Sz, *Sitophilus zeamais*; Cq, *Cathartus quadricollis*; So, *Sitophilus oryzae*; Tca, *Tribolium castaneum*; Ps, *Palorus subdepressus*; Cf, *Cryptolestes ferrugineus*; Sc, *Sitotroga cerealella*; Rd, *Ryzopertha dominica*; Ls, *Lasioderma serricorne*; Om, *Oryzaephilus mercator*; Cc, *Corcyra cephalonica*; Ec, *Ephestia* (*Cadra*) *cautella*; and Os, *Oryzaephilus surinamensis*. The ranking of insect species is based on data provided by various workers (see References).

Ghana is part of the low-latitude wet-and-dry and humid tropical lands of the world. Ghana's climate is unique, because it results from a clash of two extremely dissimilar air masses traveling diagonally from opposite directions: the cool and moist monsoon air masses, which reach Ghana from the southwest after long passage over the sea, and the hot and dry harmattan air masses, which arrive from the northeast after passage over the desert. The two air masses meet in an area known as the intertropical convergence zone (ITCZ). Their mixing generally produces an environment of warm moist air, although at times one or the other air mass may predominate. Intermittent solar radiation on this warm and moist atmosphere causes great diurnal fluctuations in relative humidity, allowing an ideal environment for fungal growth. Diurnal temperature fluctuation in the north ranges between 24 and 35°C and in the south between 23 and 31°C.

Because the bodies of cold-blooded animals assume the temperature of their immediate environment, the metabolic rate of insects in the Ghanaian environment increases with the rise in temperature at a rate dangerously higher than that with which the insect can cope. The crucial rate at which temperature affects insect survival and rate of increase can be understood by looking at the diagram (Fig. 12) that illustrates the relationship between temperature and insect development. Insect development is quickly retarded with the rise in saturation deficiency, which in turn results from increased temperature. Saturation deficiency is a measure of the vapor-pressure gradient between the transpiring insect and its environment at any temperature; it is the difference between saturated vapor pressure and actual vapor

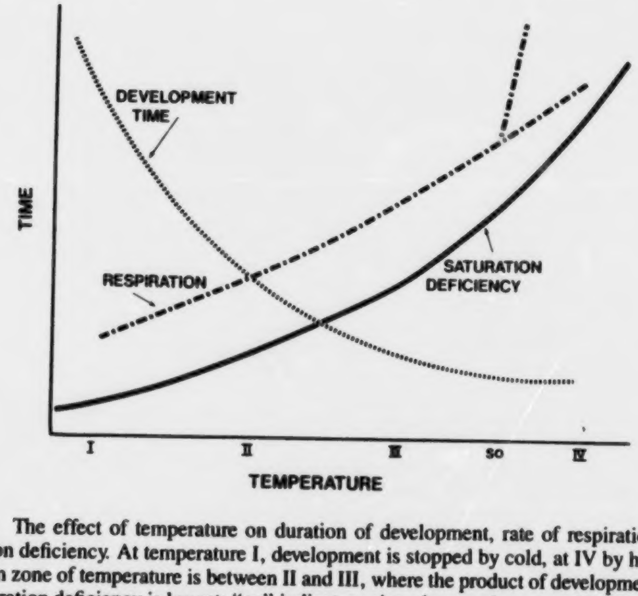


Fig. 12 The effect of temperature on duration of development, rate of respiration, and saturation deficiency. At temperature I, development is stopped by cold, at IV by heat; the optimum zone of temperature is between II and III, where the product of development time and saturation deficiency is lowest; "so" indicates spiracular opening caused by changes in temperature in certain insects.

pressure at a given temperature. The optimum for insect development in an atmosphere of constant water content, in which relative humidity declines when the temperature rises, lies near the point at which the products of development time × saturation deficiency is the lowest. The thermal death point is reached at an unbearably high level of saturation deficiency.

In Ghana, the optimum condition for the development of most storage microflora (25–35°C) falls within the normal ranges of relative humidity and temperature in the south; only certain species of insects can make best use of the Ghanaian climate.

In the north, relatively drier conditions favor *Tribolium castaneum* and *Lasioderma serricorne*, whereas in the south, more moist, relatively cool conditions favor *Sitophilus oryzae*. Laboratory findings on the rate of increase explain the reason for the climatic separation of these dominant species. Fig. 13 shows that *T. castaneum* multiplies faster at higher temperature than does *S. oryzae*.

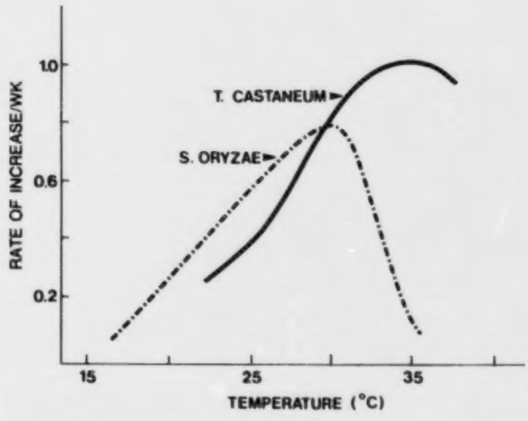


Fig. 13 The effect of temperature on the weekly rate of increase of a highly adaptable storage species (*Tribolium castaneum*) and a moderately adaptable storage species (*Sitophilus oryzae*) in Ghana.

India (middle-latitude humid lands, humid subtropical zone)

The humid subtropical zone of the middle-latitude humid lands is further divided into subclimatic regions. For example, the cereal-producing Uttar Pradesh state in the north-central part of India has six climatic zones, each with a characteristic combination of dominant stored-product insect species. In a survey of endemic insect species in empty granaries, *Sitophilus oryzae*, *Sitotroga cerealella*, *Rhyzopertha dominica*, and *Tribolium castaneum* were found to be the most common pests of paddy, wheat, corn, millet, and other grains grown in this region. Although food types and storage structures (approximate capacity 50–15 000 kg) influence species distribution, climate seems to determine the pattern of combination of major species within a region. The three dominant species (listed in order of importance) in each region are given in Fig. 14. *S. cerealella* is a dominant pest in all regions except the cool hill area (about 1000 m above sea level), in which *R. dominica* predominates. The notorious khapra beetle, *Trogoderma granarium*, is dominant in the hottest and driest region in the south, Bundelkhand. The abundance of *R. dominica* and *Oryzaephilus surinamensis* in eastern, central, and the western plain regions—this area is dominated by *Sitophilus oryzae* and *Sitotroga cerealella*—is noteworthy. Obviously, certain combinations of major pest species in a region are the result of various causes—agricultural and socioeconomic as well as climatic. But climate has a dominant influence on the other two.

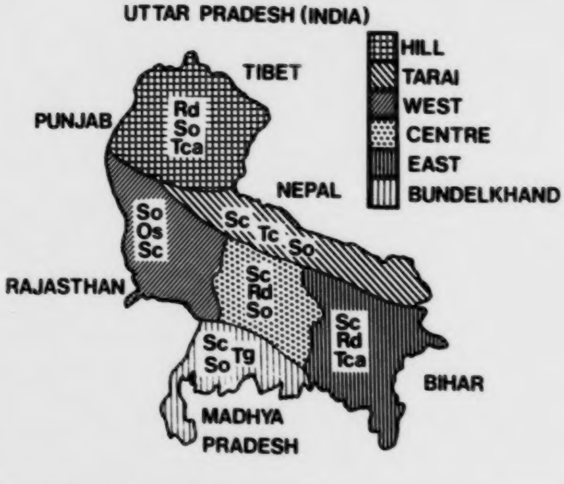


Fig. 14 Six local climatic zones in Uttar Pradesh state, India. Hill area is cooler and humid, Bundelkhand is hot and dry, and all other areas are hot and humid to wet. The abbreviations for species names are as follows: Rd, *Ryzopertha dominica*; So, *Sitophilus oryzae*; Tca, *Tribolium castaneum*; Os, *Oryzaephilus surinamensis*; Sc, *Sitotroga cerealella*; Tc, *Tribolium confusum*; and Tg, *Trogoderma granarium*.

Australia (Mediterranean and middle-latitude humid lands)

The grain-growing areas of Australia have Mediterranean and middle-latitude humid (humid subtropical and West Coast marine) climates (Fig. 15). Unlike Canada and the United States, where the warm harvest period is followed by cooler weather, the early summer harvest in Australia is followed by weeks or months of warm to hot weather. Consequently, the major insect pests of stored grain—Australia has almost all major cosmopolitan species—have a favorable environ-

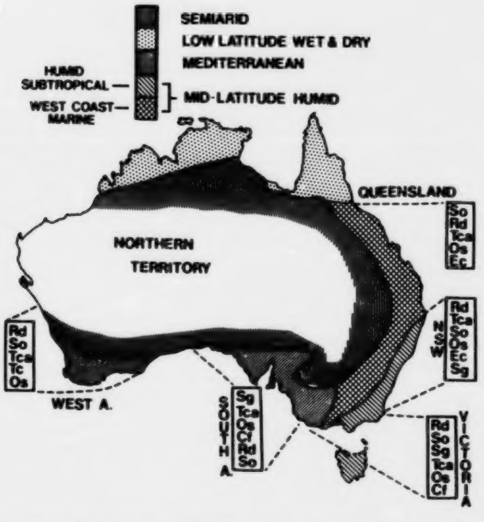


Fig. 15 Climatic zones and major stored-product insect species in Australia. The storage species were ranked by local entomologists in order of importance. The abbreviations for species names are as follows: Rd, *Rhyzopertha dominica*; So, *Sitophilus oryzae*; Tca, *Tribolium castaneum*; Tc, *Tribolium confusum*; Os, *Oryzaephilus surinamensis*; Sg, *Sitophilus granarius*; Cf, *Cryptolestes ferrugineus*; and Ec, *Ephestia cautella*.

ment to start infestations. Fig. 15 shows five combinations of storage species that are ranked according to economic importance (the data were provided by local entomologists for each of five states). In the wheat-growing parts of Western Australia, which have a Mediterranean climate (winter rainfall and dry, warm summers but influenced by the adjoining hot and dry semiarid zone), *Rhyzopertha dominica* ranks as the most serious stored-wheat pest. *Sitophilus oryzae*, *Tribolium castaneum*, and *Oryzaephilus surinamensis* follow in order of importance, but *S. granarius* is not among the major pests. In South Australia, which has a more moist Mediterranean climate, a survey by a local entomologist, Peter Birks, has shown that 40% of farms were infested with *S. granarius*, 30% with *T. castaneum*, 29% with *O. surinamensis*, 16% with *Cryptolestes* spp., 15% with *R. dominica*, and only 8% with *S. oryzae*. Victoria and New South Wales also have *S. granarius* as a high-ranking pest. It is noteworthy that *S. granarius* is not important in Queensland, which may reflect the dominance of *R. dominica* and *S. oryzae* over other stored-product insects. However, *S. granarius* thrives as a pest of New South Wales. The range of climatic conditions seems to provide perfect conditions for demonstrating the preferences of this species. This species was recently recorded on the western slopes of the Great Dividing Range, north to within 50 miles of the border with Queensland. High altitude with relatively cool and moist conditions favor *S. granarius*. A partial explanation for the success of *R. dominica* and the two weevil species also lies in the climatic effect. Most of Australia is warmer than the Prairie Provinces of Canada. Nevertheless, the highly adaptable *T. castaneum* and *Cryptolestes ferrugineus* occur in large numbers in both countries.

USSR (middle-latitude humid lands)

The climate of most of the crop-producing areas of European USSR is middle-latitude humid (humid continental), with short, hot summers and long, cold winters. Weather during harvest (usually in August) greatly affects the initial storage condition of the grain. Grain is harvested at various moisture levels in various regions of the country. The initial storage moisture content of undried grain is below 15% in northern Caucasia, the Crimea, and the southern Volga areas, which have longer and warmer summers. It increases to 16–20% as one moves northward through the Ukraine towards the Baltic Sea (Fig. 16). *Sitophilus granarius*, *Cryptolestes ferrugineus*, and grain mites are major pests in the cooler and moister northern areas, whereas *Oryzaephilus surinamensis*, *Sitophilus* spp., *Tribolium castaneum*, and *Sitotroga cerealella* are the predominant species in stored grain in the south. Climatic influence on storage insects is dramatic when one considers the number of generations per year for *Sitophilus oryzae*. This species has as many as six to seven generations in the southern areas and only one or two in the north (Fig. 16).

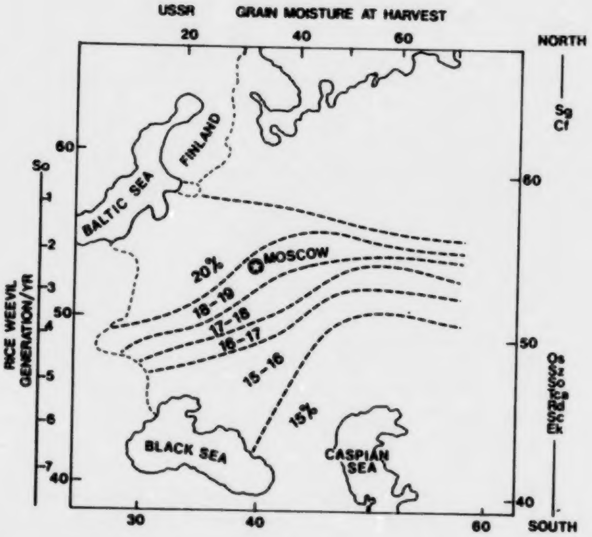


Fig. 16 The levels of grain moisture at harvest and the major stored-grain insect species in the USSR. The scale on the left indicates how *Sitophilus oryzae* has fewer generations as one moves northward. The abbreviations for species names are as follows: Os, *Oryzaephilus surinamensis*; Sz, *Sitophilus zeamais*; So, *Sitophilus oryzae*; Tca, *Tribolium castaneum*; Rd, *Rhyzopertha dominica*; Sc, *Sitotroga cerealella*; and Ek, *Ephestia kuehniella*.

Burma (humid tropical and low-latitude wet-and-dry lands)

The rice-growing areas of Burma provide optimum conditions for the development of almost all major storage insects. The mean daily temperature ranges from 25°C in January to 31°C in April. The relative humidity ranges from 61 to 68% in the relatively dry winter and is about 90% in the monsoon months of May to September. *Corcyra cephalonica*, *Sitophilus oryzae*, *Tribolium castaneum*, and *Sitotroga cerealella* are among the several dominant pests of stored grain (Fig. 17). It is noteworthy that Burma's major pest, *C. cephalonica*, is scarce in the rice-growing area of the northern hemisphere. The ubiquitous and highly adaptable species *T. castaneum* and *Cryptolestes ferrugineus* are also pests of stored grain in Burma.

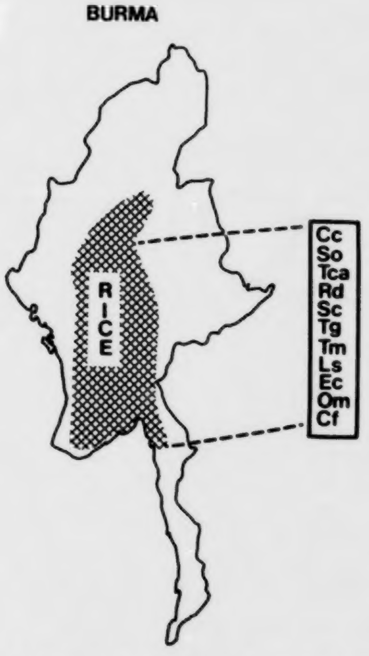


Fig. 17 The rice-growing area and the major stored-product insect species in Burma, ranked in ascending order of importance. The abbreviations for species names are as follows: Cc, *Corcyra cephalonica*; So, *Sitophilus oryzae*; Tca, *Tribolium castaneum*; Rd, *Rhyzopertha dominica*; Sc, *Sitotroga cerealella*; Tg, *Trogoderma granarium*; Tm, *Tenebroides mauritanicus*; Ls, *Lasioderma serricorne*; Ec, *Ephestia (Cadra) cautella*; Om, *Oryzaephilus mercator*, and Cf, *Cryptolestes ferrugineus*.

Argentina (middle-latitude humid lands, humid subtropical zone)

Argentina has a humid subtropical climate. Its main wheat-producing area, 1127 km between latitude 30° and 40°, is limited in the north by a combination of high temperature and high humidity in the growing season, in the west by arid desert conditions, and in the south by drought and low temperature. The winters are mild except in the southern part. Harvesting takes place in November and December. Harvested grain is stored in sacks in local granaries and warehouses, in bulks in elevators in the interior, and in large terminal elevators at the seaport. Various major storage species occur in relation to the climatic and storage conditions. A major pest is *Sitophilus granarius*, which prefers cooler climates than do other *Sitophilus* spp. It is most common in the cool southern areas, where it completes six to seven generations each year. Other major pests are *S. oryzae, Sitotroga cerealella, Rhyzopertha dominica, Tribolium castaneum, Ephestia cautella, Oryzaephilus surinamensis*, and *Cryptolestes ferrugineus*.

Canada and the United States (middle-latitude humid lands)

The climatic subdivisions, crop-growing pattern, and major pests of North America north of Mexico are given in Figs. 18 and 19. Most Canadian grain is produced in the three Prairie Provinces of Manitoba, Saskatchewan, and Alberta.

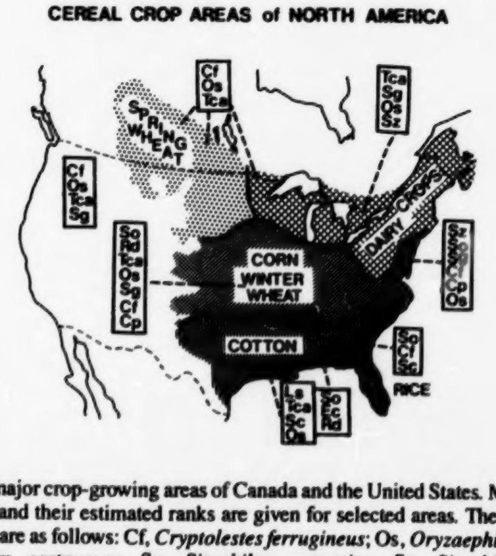


Fig. 18 The major crop-growing areas of Canada and the United States. Major stored-grain insect species and their estimated ranks are given for selected areas. The abbreviations for species names are as follows: Cf, *Cryptolestes ferrugineus*; Os, *Oryzaephilus surinamensis*; Tca, *Tribolium castaneum*; Sg, *Sitophilus granarius*; So, *Sitophilus oryzae*; Rd, *Rhyzopertha dominica*; Cp, *Cryptolestes pusillus*; Ls, *Lasioderma serricorne*; Sc, *Sitotroga cerealella*; Ec, *Ephestia cautella*; and Sz, *Sitophilus zeamais*.

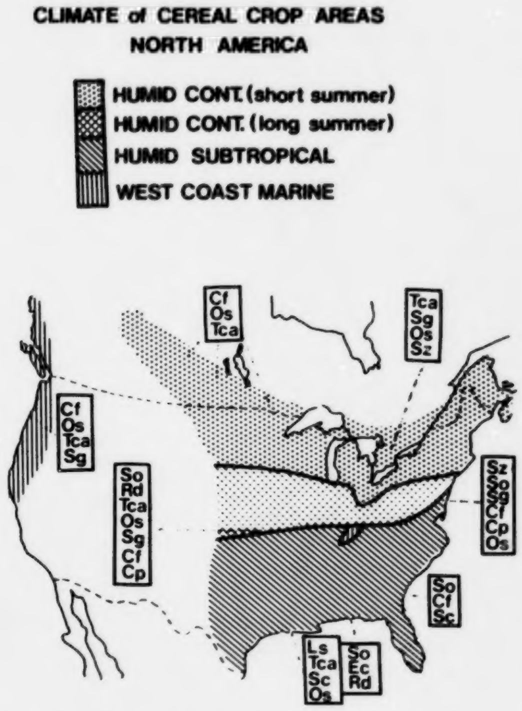


Fig. 19 The climatic areas of Canada and the United States. Major storage insect species and their estimated ranks are given for selected areas. The abbreviations for species names are as follows: Cf, *Cryptolestes ferrugineus*; Os, *Oryzaephilus surinamensis*; Tca, *Tribolium castaneum*; Sg, *Sitophilus granarius*; So, *Sitophilus oryzae*; Rd, *Rhyzopertha dominica*; Cp, *Cryptolestes pusillus*; Ls, *Lasioderma serricorne*; Sc, *Sitotroga cerealella*; Ec, *Ephestia cautella*; and Sz, *Sitophilus zeamais*.

The Canadian prairies have a humid continental grassland type of climate; the winters are long and cold, the summers short and hot. Harvesting takes place during August and September. In winter, temperature (direct exposure without insulation by grain mass) often falls below the minimum limits of reproduction, development, and survival of most destructive cosmopolitan stored-grain species and exceeds the maximum limits for certain species in summer. Only cold-hardy and adaptable species, such as *Cryptolestes ferrugineus*, *Tribolium castaneum*, and *Oryzaephilus surinamensis*, which can take advantage of a sheltered granary environment, can flourish in this climate (Fig. 19). The area of Washington that produces winter wheat and the states that grow spring wheat (North Dakota and Minnesota) have the same combination of pest species in farm-stored grain. However, because the climate of Washington is milder and more moist, *Sitophilus* *granarius* is also found there. The states that grow winter wheat, such as Kansas, and the states that grow both wheat and corn, such as Iowa, Illinois, and Indiana, have a combination of major pests that includes *Sitophilus oryzae*, *Rhyzopertha dominica*, and *T. castaneum*. In the corn belt, *S. zeamais* is a dominant insect pest. In the southerly humid subtropical areas along the Gulf Coast, *Lasioderma serricorne*, *T. castaneum*, *Sitotroga cerealella*, *O. surinamensis*, and *Sitophilus oryzae* are among the top-ranking pests.

Interference of climatic effect

Although climatic data for a geographical location give an estimate of the performance of stored-product insects in that area, allowances must be made for the factors that usually reduce the impact of a climatic variable. The size of the grain bulk and the granary structure are two such important factors. The larger the bulk grain the greater is the protection of insects from weather and climate. Thus climatic effect becomes most pronounced in small granaries. By computer simulation of temperature data in circular metal granaries of various sizes filled with wheat, it was shown that the temperature effect was most pronounced in granaries that were up to 4 m in diameter. When freshly harvested grain is stored at 25°C in Winnipeg, it takes 90 days for the center of a bin 4 m in diameter to cool below 20°C. The comparable figure for a bin 6 m in diameter is 150 days; 8 m, 225 days; 10 m, 329 days; and 12 m, 553 days. Grain cools fastest and remains cool longest in regions such as Winnipeg and Thunder Bay, which have a temperate climate. The milder climate of coastal cities such as Montreal and Vancouver is reflected in the slower cooling of the grain.

CHAPTER 3 GENERAL CHARACTERISTICS OF INSECTS

Insects (Class Insecta) are the most successful pests of stored crops and their products. To control or prevent insect infestation, one should have some knowledge of their structure, function, and major characteristics. Only by having a thorough appreciation of the biology of insect pest species can one develop effective strategies for their successful control. Most adult insects are easily distinguished from other animals by their characteristic structure: three pairs of segmented legs (each leg usually having five segments); three distinct body parts (head, thorax, and abdomen); a pair of feelers (antennae); and one or two pairs of wings.

As a group, insects are truly ancient, having lived continuously for about 350 million years, compared with less than 2 million years for humans. Insects are the most common and widespread of all animals that live on earth. They comprise about 900 000 of the estimated total of 1.6 million living animal species that have been described. To become the dominant group of animal species in the dry, terrestrial environment of the earth, insects have fully used the mechanical advantage of a hard, chitinous body covering (exoskeleton). The exoskeleton provides the means for the internal muscle attachment required for movement and flight, it is a near perfect enclosure for reducing water loss, and it protects vital organs from injury. The survival and success of insects over other competitors are attributable to six major specializations: power of flight with functional wings, small size, structures adapted for various special functions, complete metamorphosis (fundamental changes in form through four life stages), high fecundity, and a highly evolved ability to adapt.

To facilitate the study and control of insects, all species of this group have been systematically classified. For example, the red flour beetle, *Tribolium castaneum* (Herbst), is a part of the animal kingdom. But its precise rank, according to the well-established binomial system of nomenclature devised by the Swedish naturalist Linnaeus, is as follows: phylum: Arthropoda (joint-legged invertebrates); class: Insecta (Hexapoda); order: Coleoptera; family: Tenebrionidae; genus: *Tribolium*; species: *castaneum*; and authority (the surname of the person describing the species): (Herbst).

It is a common practice throughout the world to write the scientific name of the genus and the species in italic type. The first letter of the genus (but not of the species) is written with a capital letter. If the name of the person who described the species is in parentheses, the species was originally described in association with another genus. A similar practice is not applicable to its common name, which may or may not vary from one country to another. For example, the common name for *T. castaneum* is red flour beetle in North America and rust-red flour beetle in Britain. The main structural characters of insects are external and internal morphology.

The external morphology of an insect consists of a three-part body, which contains a distinct head, thorax, and abdomen. The head contains one pair of antennae. The mouth parts are for chewing, sucking, or lapping and consist of mandibles (true jaws with teeth), maxillae (accessory jaws), a labrum (upper lip), and a labium (lower lip). The thorax (composed of three somites, or segments) has three pairs of jointed legs and usually has two pairs of wings. A leg is composed of the following: coxa (the basal segment), trochanter, femur, tibia, and tarsus (foot). The abdomen has 11 or fewer segments; its terminal part is modified as genitalia.

The internal morphology of insects consists of the alimentary canal, which contains a mouth with salivary glands, foregut, midgut, and hindgut. The heart is slender with lateral ostia (an opening usually guarded by a valve) and an anterior aorta without veins or capillaries. The body spaces form a hemocoel (part of the body cavity functioning as a part of a blood–vascular system). Respiration usually occurs through branched, chitin-lined tracheae (air tubes) that transport oxygen, from paired spiracles (air openings) on the sides of the thorax and abdomen, directly to the tissues. The nervous system is composed of supraesophageal and subesophageal ganglia connected to a double, ventral nerve cord, usually with one pair of ganglia per segment. The sense organs include compound and simple eyes (ocelli), chemoreceptors (for smell on the antennae and for taste around the mouth), and various tactile hairs. The senses are separate.

The reproductive system includes the gonads, which consist of multiple tubules with one median duct running posteriorly. Fertilization is internal. The ova are yolk-filled with protective shells. Development occurs through a process called metamorphosis, which involves a series of changes through which an insect passes in its growth from egg to adult. Complete metamorphosis involves several larval stages, a resting pupa, and an adult. Incomplete metamorphosis involves several immature nymphal stages that resemble the adult. Parthenogenesis (asexual reproduction) occurs in some insect species.

Many of approximately 600 species of insects that have been associated with stored products belong to the order Coleoptera (beetles). The second order that contains many stored-product pests is the Lepidoptera (moths and butterflies). Other orders that include stored-product pests are Psocoptera (psocids or book lice), Thysanura (bristletails, e.g., silverfish), and Dictyoptera (cockroaches). In addition, mites belonging to the class Arachnida, order Acarina, are also common and are often important pests of stored crops and their products. Mites can be distinguished from insects by their smaller size (usually less than 1 mm) and sac-like, compact body in which are found a cephalothorax and an abdomen with no segmentation. Most mites have four pairs of legs in the adult and nymphal stages and three pairs in the larval stage, which immediately follows the egg stage.

Order Coleoptera (beetles)

Beetles are the most common and important pests of stored products. With over 330 000 described species, Coleoptera is also the largest order in the class Insecta. Although many beetle species have been associated with stored products, only about 25 are considered to be important pests. Adult beetles may be distinguished by their thickened, hard, and brittle fore wing, called an elytron, or wing cover. A pair of elytra usually meet in a straight line down the middle of the back over the abdomen and cover the usually folded membranous hind wings (often reduced). The antennae are ten- or eleven-segmented and variable, usually threadlike, clubbed, or geniculate (elbowed). The mouth parts are of the chewing type. The tarsus of the legs usually has five segments, but often only three or four. Beetles have four distinct life stages: egg, larva, pupa, and adult.

Beetle larvae (grubs) possess the following distinguishing characters: a distinct small head, darker than the rest of the body, which is usually white or yellowish; well-developed biting mouthparts; one to six simple eyes or ocelli on each side of head, which lacks compound eyes; a thorax that includes three pairs of legs; and an abdomen that contains no paired false legs (pseudopods). Variation occurs in weevil larvae (family Curculionidae), which are legless; they are stout and short and their mandibles bite horizontally. The legless larvae of Diptera (flies) have a distinct head; they may occur in decaying stored products and may be confused with beetle larvae. Diptera larvae (maggots) are long and narrow, and their mandibles bite vertically. Some important families of Coleoptera that infest stored products are Tenebrionidae, Curculionidae, Cucujidae, Bruchidae, Dermestidae, Bostrichidae, Nitidulidae, Ptinidae, and Lathridiidae.

The developmental period of the Coleoptera that infest stored products varies from a few weeks to more than a year. The larval developmental period in some species is considerably longer than that of the other stages. Generally, larvae cause greater damage to stored food than do adults.

In addition to destroying stored crops directly by feeding, beetle species can cause heating and moisture accumulation in bulk stored food by the respiration of large populations. Such heating, popularly called "hot spots", can cause the lowering of grain quality and spoilage by reducing germinability of seeds, increasing fungal and bacterial infection, charring the seeds, and increasing the free fatty acid levels of the food products. The extent of food damage varies with the insect species, its rate of increase, the voracity of the larvae, and the temperature, moisture, and nutritive value of the stored food.

Order Lepidoptera (moths and butterflies)

Of about 165 000 species of Lepidoptera described, only a handful are pests of stored products. Lepidopteran adults vary in size. Larval mouth parts are for chewing, and those of adults are for sucking liquids through a tubular tongue, or proboscis. The antennae of adults are long. There are two pairs of membranous wings, which are usually broad with a few crossveins and covered by microscopic overlapping scales; the body is scaly or hairy; coloration varies from dull to brilliant. Larvae or caterpillars have a well-developed head, three thoracic segments, and 10 abdominal segments. The larvae are wormlike, with three pairs of five-segmented, thoracic legs and seven pairs of prolegs (pseudopods) on the third to the sixth and on the tenth abdominal segments. Each proleg has several curved apical teeth (crotchets), which are usually arranged in a circular fashion. The larvae have two silk glands on the labium, which are used to spin a cocoon to contain the pupa. Lepidopteran species that infest stored crops are all moths, which are usually active at night. Although short-lived (about 4–10 days), moths are easy to identify, and destruction of stored products is caused exclusively by their larvae.

After mating, the female moth deposits eggs in or on foodstuff on which larvae feed. The larvae spin abundant silk, which may provide the first visible warning sign of infestation. The excreta and frass often remain woven in the silken web. Full-grown larvae seek out cracks and crevices in which to pupate. All pupae of stored-product moths are enveloped within a silken cocoon built by the larvae for pupation. In warm granaries and warehouses, Lepidoptera may have several successive generations without regard to seasonal weather changes. Some species undergo diapause or a dormant inactive stage during a part of the year.

Order Psocoptera (psocids, or booklice)

Psocids are small to minute, relatively simple, fast-moving insects. Many species of this group infest stored products, although they may not be economically important. The antennae are long, slender, and threadlike, with 13–50 segments. The mouth parts are of the chewing type. The prothorax is small. Some species have four membranous, veined wings and others (including several stored-product species) have none. At rest, the wings are roofed over the abdomen. The females have no ovipositor. Metamorphosis is incomplete or is lacking, because the young forms are similar to the adults and they lack wings. Small (about 1 mm), dark brown, gray, or yellowish white insects are found in large numbers in aging bulk grain or grain products and flour, particularly when they are moldy or damp. Psocids feed on seed-borne fungi and grain dust; these insects spoil grain by contaminating it with excrement. Their presence in stored products is an indicator of deterioration.

Order Hymenoptera (bees, wasps, and ants)

Hymenoptera includes not only bees and ants but also several parasitic wasps that attack the larvae of many stored-product beetles and moths. Generally, adult Hymenoptera have two pairs of membranous wings, but some parasitic wasps are wingless. Their mouth parts are of the chewing or chewing-lapping type. The females often have a short or long ovipositor for sawing, piercing, or stinging. The larvae are caterpillar-like or legless. The pupae usually remain in cocoons. Metamorphosis is complete, with egg, larval, pupal, and adult stages. Most species are solitary, but some are social and live in colonies; others, such as those associated with stored-product insects, are parasitic as larvae and develop inside other insects. Adult parasitic wasps are small (about 1 mm) and often occur in large numbers on the windows and doors of granaries and warehouses containing insect-infested produce. The presence of these insects usually indicates infestation by a particular beetle or moth host species. Some of the common hymenopterous parasites of stored-product insect pests are: *Bracon hebetor* Say (family Braconidae), *Cephalonomia waterstoni* Gahan (family Bethylidae), and *Holepyris hawaiiensis* (Ashmead) (family Bethylidae).

CHAPTER 4 BIOLOGICAL AND ECOLOGICAL FEATURES OF STORED-PRODUCT INSECTS

Although a considerable amount of information on the distribution, biology, and ecology of about 100 species of stored-product insect pests of the world is now available, this information is not often usable for the following reasons: it is scattered throughout the literature in many languages; not all data are equally reliable; and some results have been published under different synonyms of an insect species. Table 1 provides an alphabetical list of 106 insect species associated with stored products. The nine columns of the table provide a reasonably reliable factual summary based on published information on the distribution, pest status, food habits, and important biological and ecological aspects of each insect species. Although the table was reviewed by several stored-product entomologists (see Preface), all data presented here have not necessarily been verified or approved by each specialist. In some cases, arbitrary decisions had to be made with regard to both nomenclature and conflicting results of scientific studies.

Table 1 column headings

Single or multiple notations and figures are used for many species in most columns. This lack of uniformity is a result of the compilation of fragmentary experimental data from various sources. Emphasis is placed on recording accurate data, regardless of the extent of their completeness.

Geographical distribution

Because all stored-product insect species are potentially capable of spreading from one continent (or country) to another through modern global transportation systems, no single species can be considered truly regional on the basis of single or repeated incidences. Therefore, the species incidence reports in this table have been arbitrarily classified as cosmopolitan or have been placed in two broad climatic zones—temperate and tropical–subtropical. When records of repeated occurrence of a species are also associated with reports of survival, overwintering, and multiplication in stored products in one zone but not in others, the species is then considered restricted to only one zone.

Pest status

The pest status categories are based mainly on the categories designated by authorities from two sources, Cotton and Wilbur (1974) and Prevett (1970).

Table 1. Insects associated with stored products

Species	Geogr. distrib.*	Pest status†	Crop infested‡	Dev. temp. (°C)§	Dev. RH (%)§	Dev. time (days)	Adult longevity (days)	Rate of increase (every 4 wk)	Climatic plasticity index (I_p)
Acanthoscelides obtectus (Say)	C	1	P	R 15–34 F 30	R 30–90 F 70–80	30	4–37	25	275
Ahasverus advena (Waltl)	C	2	C,O,V,P	25–30	R 60–100	17–24	275–301		
Alphitobius diaperinus (Panzer)	C	2	C,V	25–35	F 80–95	35			
Alphitobius laevigatus (Fabricius)	C	2	C,V	25–35	F 80–95	35			
Alphitophagus bifasciatus (Say)	C	2	V	25					
Anthrenus verbasci (Linnaeus)	Te, C	2	V,C	22		251–351	13–44		
Aphomia gularis (Zeller)	C	2	D,V,C	22					
Araecerus fasciculatus (De Geer)	Tr, C	1	P,V,D,C	M 22 F 28–32	M 65 R 50–100 F 80	49	40–60	40	360
Attagenus pellio (Linnaeus)	Te	2	V,C	22		365+			

Attagenus *unicolor* (Brahm)	C	2	V,C	22–25		272–694	14–38		
Bruchus *pisorum* (Linnaeus)	C	1	P			60	730		
Bruchus *rufimanus* Boheman	Tr	1	P						
Callosobruchus *analis* (Fabricius)	Tr	1	P	R 22–35 F 30–33	M 1 F 70	26–94	5–59	25	
Callosobruchus *chinensis* (Linnaeus)	Tr, Te	1	P	R 19–33 F 28–32	R 30–100 F 90			30	315
Callosobruchus *maculatus* (Fabricius)	C	1	P	R 18–35 F 30–32	R 10–90 F 70	21–170	5–46	50	550
Callosobruchus *rhodesianus* Pic	Tr	1	P	M 16 F 27–31	M 1 F 70	25–107		20	230
Carpophilus *dimidiatus* (Fabricius)	C	2	D,V,C,O	M 6 F 33	R 70–100	15			
Carpophilus *freemani* Dobson	Tr	2	D,V,C						
Carpophilus *hemipterus* (Linnaeus)	C	2	C,D,O,P,V	M 19 F 31–34	M 50	16–125	365	50	550
Carpophilus *ligneus* Murray	C	2	D,V						
Carpophilus *lugubris* Murray	Tr	2	D,V,C			14			

Table 1. **Insects associated with stored products** *(continued)*

Species	Geogr. distrib.*	Pest status†	Crop infested‡	Dev. temp. (°C)§	Dev. RH (%)§	Dev. time (days)	Adult longevity (days)	Rate of increase (every 4 wk)	Climatic plasticity index (I_p)
Carpophilus maculatus Murray	C	2	C,O,D,V						
Carpophilus marginellus Motschulsky	C	2	V,D						
Carpophilus mutilatus Erichson	Tr	2	D			14			
Carpophilus obsoletus Erichson	Tr		D,C,V,P			60–90	168–207		
Carpophilus pallipennis (Say)	Tr	1	C,V						
Caryedon serratus (Olivier)	Tr	1	P,O,V	M 22 F 28–30	M 30 F 70	42		6	42
Cathartus quadricollis (Guérin-Méneville)	C	2	C	28		21			
Caulophilus oryzae (Gyllenhal)	C	2	C,V			30	152		
Corcyra cephalonica (Stainton)	C	1	C,D,O,V	R 17–35 F 28–32	R 15–90 F 70	28–93	3–22	10	110
Cryptolestes capensis (Waltl)	C	2	C,P,V	M 18 F 27–31	M 1			10	105

Cryptolestes *ferrugineus* (Stephens)	C	1	C,O,V	R 20–40 F 33	R 40–95 F 70–80	21	180–270	60	570
Cryptolestes *pusilloides* (Steel & Howe)	C	2	V,C	M 18 F 27–31	M 60		180–270	10	105
Cryptolestes *pusillus* (Schönherr)	C	1	C,V,P	R 18–38 F 28–33	R 45–100	22–43	80–600	10	100
Cryptolestes *turcicus* (Grouvelle)	C	1	C,V	M 21 R 18–38 F 30–35	R 45–100 F 90	30	180–270	50	475
Cryptolestes *ugandae* (Steel & Howe)	Tr		C,P,V	M 20 F 28–32	M 50	15			150
Cynaeus *angustus* (LeConte)	Te	2	V,C	F 30	F 73	53–65			
Dermestes *ater* De Geer	C	2	C,V	F 27–29		37–53	90		
Dermestes *frischi* Kugelmann	C	3	V	M 22 F 31–34	M 50		90	30	285
Dermestes *lardari*[illegible] Linnaeus	C	2	V	F 18–20		45–60	60–90		
Dermestes *maculatus* De Geer	C	3	V	M 20 F 30–35	M 30 F 70	44–70	90	30	360
Endrosis *sarcitrella* (Linnaeus)	Te, C	2	C,V,P,D	M 10 F 24–26	M 80	56		30	330

Table 1. Insects associated with stored products *(continued)*

Species	Geogr. distrib.*	Pest status†	Crop infested‡	Dev. temp. (°C)§	Dev. RH (%)§	Dev. time (days)	Adult longevity (days)	Rate of increase (every 4 wk)	Climatic plasticity index (I_p)
Ephestia calidella (Guenee)	C	1	P,D	R 14–30 F 25–30	R 20–90 F 70	24–80		20	230
Ephestia cautella (Walker)	C	1	C,D,V	M 15 F 28–32	R 20–90 F 70	25–145	2–26	50	575
Ephestia elutella (Hübner)	C	1	V,C,D,O	M 10 F 25	M 30 F 70	29–383	4–16	15	165
Ephestia figulilella Gregson	C	2	D,V,C	R 17–30 F 30	F 70–90	24–139	11–16		
Ephestia kuehniella Zeller	C	1	V,C,D,P	R 12–30 F 24–27	R 0–80 F 75	30–420	7–21	50	600
Gibbium psylloides (Czenpinski)	C	3	V	M 20 F 31–34		45	120–730	4	42
Gnatocerus cornutus (Fabricius)	C	1	V,C,O	M 16 F 24–30	M 40	57	365	15	180
Gnatocerus maxillosus (Fabricius)	Tr	2	V,C	R 18–35 F 24–30	R 6–100	34–40	365		
Haptoncus luteolus (Erichson)	Tr	2	D,V			14			
Hofmannophila pseudospretella (Stainton)	Te	2	C,P,D,V	M 13 F 24–26	M 80	365	7–12	2	19

Lasioderma *serricorne* (Fabricius)	C	2	P,C,V,O	R 20–37 F 30	R 22–100 F 70	26–105	6–42	20	200
Latheticus *oryzae* Waterhouse	C	2	V,C,D	M 26 F 33–37	M 30 F 70	29–37		10	95
Lathridius minutus (Linnaeus)	Te	2	V	27	80	24-30			
Liposcelis *bostrychophilus* Badonnel	C	2	V,C	27	70	21–23	72–144	22.5	
Lophocateres *pusillus* (Klug)	Tr	2	P,C,V,D	M 17.5 F 30	75	70			
Lyctus *brunneus* (Stephens)	C	3	V			90–365			
Mezium *affine* Boieldieu	Te	3	V	M 30 F 29–33	R 30–80		180–730	2.5	24
Mezium *americanum* (Laporte)	C	3	V	25	R 50–90		180–730		
Mycetaea *hirta* (Marsham)	Tr	2	V,C						
Necrobia *ruficollis* (Fabricius)	C	2	V,O,D	M 8		30–150	45–225		
Necrobia *rufipes* (De Geer)	C	2	V	M 22 F 30–34	M 50	30–45	420	25	250
Nemapogon *granella* (Linnaeus)	Te	1	C,V	R 7–27 F 25	R 65–95 F 90	70	14–20		

Table 1. Insects associated with stored products *(continued)*

Species	Geogr. distrib.*	Pest status†	Crop infested‡	Dev. temp. (°C)§	Dev. RH (%)§	Dev. time (days)	Adult longevity (days)	Rate of increase (every 4 wk)	Climatic plasticity index (I_p)
Niptus hololeucus (Faldermann)	Te, C	2	V,C	M 10 F 19–23	M 50		180–730	2	21
Oryzaephilus mercator (Fauvel)	C	1	P,C,V,D	R 18–38 F 30	R10–90 F 70	25	180–300 (up to 1080)	20	210
Oryzaephilus surinamensis (Linnaeus)	C	1	C,V,P,D	R 18–37.5 F 31–34	R 10–90 F 90	20	180–300 (up to 1080)	50	500
Palorus ratzeburgi (Wissmann)	C	2	C,P,O,D,V	R 17–37 F 27–35	R 20–90 F 50–80	25–114	60–90		
Palorus subdepressus (Wollaston)	C	2	C,V	M 17.5 R 17–35 F 30–32	R 50–90 F 80	30–141			
Pharaxonotha kirschi Reitter	Tr	1	C,V			32–145			
Platydema ruficorne (Sturm)	Te	2	C,V						
Plodia interpunctella (Hübner)	C	1	C,O,D,V	R 18–33 F 26–29	R 25–95 F 70	26	5–13	30	330
Prostephanus truncatus (Horn)	Tr	1	C	R 18–37 F 25–32	R 40–90 F 80	24–167	45–168	25	

Pseudorostus *hilleri* (Reitter)	Te		V	M 15 F 19–21	M 50		180–730	2.5	15
Ptinus *clavipes* Panzer	C	2	V	M 10 F 20–27	M 50 F 70	180–270	180–730	1+	10
Ptinus *fur* (Linnaeus)	C	2	V,C	M 10 F 21–25	M 50 F 70	132–358		2	23
Ptinus *ocellus* Brown	C	2	V,D,P	M 10 F 20–25	M 50 F 80–90	67	180–730	4	42
Ptinus *pusillus* Sturm	Te	2	V	M 19 F 22	M 50		180–730	1+	5
Ptinus *sexpunctatus* Panzer	C	2	V	M 19 F 26–30	M 50		180–730	1+	9.5
Ptinus *villiger* (Reitter)	Te	2	V,C	M 10 F 20–25	M 40 F 80–90	58	180–730		
Pyralis *farinalis* (Linnaeus)	C	2	C,V,P	27–30	70–80	42–56	7–21		
Pyroderces *rileyi* (Walsingham)	Tr	1	C,V						
Rhyzopertha *dominica* (Fabricius)	Tr, C	1	C,V,P	R 18–39 F 32–34	R 25–70 F 50–60	25	120–240	20	190
Sitophilus *granarius* (Linnaeus)	Te	1	C	M 15 F 26–30	M 50 F 70	28–43	100–432	15	172.5
Sitophilus *oryzae* (Linnaeus)	C	1	C,P	R 17–34 F 26–31	R 45–100 F 70	24–96	150–730	25	275

Table 1. Insects associated with stored products *(continued)*

Species	Geogr. distrib.*	Pest status†	Crop infested‡	Dev. temp. (°C)§	Dev. RH (%)§	Dev. time (days)	Adult longevity (days)	Rate of increase (every 4 wk)	Climatic plasticity index (I_p)
Sitophilus zeamais Motschulsky	C	1	C	R 17–34 F 27–31	R 45–100 F 70		80–150	25	
Sitotroga cerealella (Olivier)	C	1	C	R 16–35 F 26–30	R 25–80 F 75	30–63	10–30	50	550
Stegobium paniceum (Linnaeus)	C	2	C,V	R 15–35 F 25–28	R 30–100 F 95	40	13–85	7.5	67.5
Stethomezium squamasum Hinton	Tr	2	V	M 19 F 25–29	M 50		180–730	3	21
Tenebrio molitor Linnaeus	C	2	C,V	R 18–30 F 24–27	R 60–95 70	120–1080	15–90		
Tenebrio obscurus Fabricius	C	2	C,V	25			15–90		
Tenebroides mauritanicus (Linnaeus)	C	1	C,D,V	M 15 F 28–30	F 70–80	70–400	180–660		
Thylodrias contractus Motschulsky		3	V			365	1080–1460		
Tipnus unicolor (Piller & Mitterpacher)	Te	2	V,C	M 12 F 16–18	M 60 F 80–90		180–730	1.5	9

Tribolium audax Halstead	Te	2	V,C	21–35 32	50–72	41–80	68–97		
Tribolium castaneum (Herbst)	C	1	O,C,V	R 20–40 F 32–35	R 10–95 F 70–75	20–30	335–540	70	700
Tribolium confusum Jacquelin du Val	C	1	C,V	R 20–38 F 30–33	R 10–100 F 70	20–54	730–1080	60	570
Tribolium destructor Uyttenboogaart	C	1	V,C	R 13–30 F 30–32	R 10–99 F 70–75	28–212	290–1460		
Tribolium madens (Charpentier)	C	2	C,V	R 22–35 F 30–35	R 10–90 F 65–90	25–30			
Trigonogenius globulus Solier	Te	3	V	M 18 F 22–24	M 50		180–730	2.5	15
Trogoderma glabrum (Herbst)	Te	2	C,V,P	F 27–38		50			
Trogoderma granarium Everts	C	1	O,C	R 24–41 F 33–37	R 1–73 F 25	25–310	3–19	12.5	131
Trogoderma variabile (Ballion)	Te	2	C,D,P,V	R 17.5–37.5 F 30	F 70	45	8–58		
Typhaea stercorea (Linnaeus)	C	2	V,C,D,P						
Urophorus humeralis (Fabricius)	C	2	D,V,C	32		16	64		

Table 1. Insects associated with stored products *(concluded)*

Species	Geogr. distrib.*	Pest status†	Crop infested‡	Dev. temp. (°C)§	Dev. RH (%)§	Dev. time (days)	Adult longevity (days)	Rate of increase (every 4 wk)	Climatic plasticity index (I_p)
Zabrotes subfasciatus (Boheman)	Tr	1	P	R 20–35 F 29–33	R 10–90 F 70	24–100	4–65	20	190

* C, cosmopolitan; Te, temperate; Tr, tropical–subtropical.

† 1, primary; 2, secondary; 3, other association.

‡ C, cereals; P, pulse crops or beans; O, oilseeds; D, dried fruit; V, miscellaneous food and fungi.

§ M, minimum; R, range; F, optimum.

Crop infested

Each species of stored-product insect is grouped under one or more of five classes, although any one species can feed on or can be associated with more than one kind of harvested crop, microflora, or debris. Cereals include starchy grain crops such as wheat, barley, corn, rice, and their products. Pulses include beans and other leguminous seeds. Oilseeds include vegetable-oil-producing crops, such as rapeseed and sunflower seed. Dried fruits include crops such as dates and raisins. Miscellaneous food and fungi include various stored products, fungi, debris, and other decaying organic products. The most commonly preferred food category is given first.

Developmental temperature

Wherever available, the temperatures (in degrees Celsius) required for insects to complete life-stages from egg to adult are given. The capital letters preceding the temperature indicate the minimum, the range, and the optimum (one figure or a range of two figures). Absence of a letter symbol indicates that only one temperature or one set of temperatures was reported in the literature.

Developmental relative humidity

Whenever it was available, relative humidity is given for the environment at which development of the species is known to be completed, measured from egg laying to adult emergence. The absence of a letter symbol means that limits were not established.

Developmental time

Developmental time from egg to adult stage is given in days. The use of two figures indicates the range of developmental times under conditions that are favorable or within which complete development is possible. The use of only one figure indicates that only one statistic, presumably obtained under favorable conditions, has been reported in the literature.

Longevity of adults

Survival time for adults from emergence until death is given in days. The use of one figure indicates the average survival under favorable conditons. The use of two figures indicates the range of survival under favorable conditons when survival time differs between sexes, or when conditions may become unfavorable, causing insects to overwinter or become dormant.

Rate of increase

Whenever it was available, the rate of increase per lunar month (28 days) is given for each species.

Climatic plasticity index

The climatic plasticity index (range 1–700) describes the potential ability of a species to adapt to various climatic regions of the world and is based on laboratory data on finite rate of increase (λ) and physical limits (temperature and relative humidity) for survival and development. The higher the index is, the greater is the bioclimatic adaptability of the species. For further explanation see Chapter 2.

CHAPTER 5 PHYSICAL AND CHEMICAL CONTROL OF STORED-PRODUCT INSECTS

Some of the fumigants mentioned in this chapter and in subsequent chapters have been suspended from use in Canada since the submission of this manuscript, these being carbon tetrachloride, carbon disulfide, ethylene dichloride, and ethylene dibromide. Furthermore, the suspension of the remaining fumigants is currently under review. Their description in the text has been left intact because a decision on their status is pending.

Grain-handling and grain-processing machinery in terminal elevators, flour mills, and other cereal-processing plants provide food and shelter for a wide variety of pests of cereals and cereal products. Control of these pests is essential for preventing infestations of grain or grain products that move through grain-handling and grain-processing facilities. High sanitation standards require that no pests occur in products destined for domestic or export markets. The type of control selected depends on pest species, numbers found, location and distribution, and season.

Physical control

Temperature is an important physical factor used to control stored-product insects, especially in temperate climates. Temperatures below the reproductive, developmental, and activity thresholds of insect pests deter infestations in premises where grain and processed foods are stored. At 12–15°C the adults of most stored-product insects cease to lay eggs, and most eggs laid at higher temperatures fail to hatch at 15°C. Larval development and locomotor activity are depressed at 5–10°C; at sub-zero temperatures, pupae of dermestid beetles go into diapause and adults of many species take several weeks to die; some may survive temperatures near 0°C. During January in the Canadian Prairie Provinces, "freeze-outs" in flour mills have proven effective in controlling infestations in milling equipment. Freeze-outs are so effective in some mills that they are often used as an alternative to chemicals for insect control. To be fully effective, however, all parts of the milling system must be exposed to the low temperatures, usually below –20°C, or the mill will become reinfested with survivors from warmer sections of the mill.

Hygiene and sanitation are important plant management practices that must be combined with physical or chemical methods of pest control. Removal of dust and cereal debris from floors, structural surfaces, and equipment denies insects access to food and shelter and prevents insect infestations of milling equipment. Commercial vacuum cleaners are recommended for this purpose. Infested debris removed by sweeping or vacuuming should be fumigated prior to its disposal to prevent insects from reinfesting milling equipment.

Centrifugal impact machines (Entoleter®) are widely used in flour mills to kill insects. The wheat or flour is fed into the central rotor of the machine and flung outward by centrifugal force to strike studs that may be stationary or rotating. The force of impact shatters insects at all stages, thus eliminating infestation. Entoleters® are manufactured in various designs according to the specific needs of a milling operation. Those used at the beginning of the milling process usually operate at slower speeds (1750 rpm) than those used to treat the finished product (3500 rpm). Infested kernels that have been structurally weakened by insect feeding are broken when passed through an Entoleter®. The broken particles and insect fragments are removed by aspiration.

Turning infested grain or transferring it to empty bins has been used extensively to reduce the severity of infestations. Certain stages of insects and mites may not survive the physical stress of movement and abrasion, and limited control is achieved by this method. An important result of turning grain is the disruption of pockets of infestation, which, if left undisturbed, produce heat through pest respiration, a requirement for optimum growth and reproduction. Infestations are thereby distributed to other locations throughout the grain bulk where environmental conditions may be less favorable for insect development and reproduction.

Insect-resistant containers provide important physical means of protecting stored grain and milled cereals from infestation. Woven polypropylene bags have been used to prevent infestation of rice by insects and rodents. Food packages or package overwraps made from cellophane, polypropylene, aluminum–film laminates, and polyethylene provide some protection to enclosed foods from insect infestation.

Several forms of radiation have been used on a commercial scale to control stored-product insects. Nonionizing radiation in the form of infrared and radiofrequency energy is used to heat infested foods to temperatures that are lethal to all species of insects at all stages of development. Light energy in the visible and invisible regions of the electromagnetic spectrum is used to control the activity of insect pests by attracting them to various types of insect traps or by influencing their activity in other ways.

Ionizing radiation in the form of gamma rays produced by the nuclear disintegration of radioactive isotopes such as cobalt 60, or high-speed electrons emitted from a heated cathode and accelerated in an electromagnetic field, have been used to control insects in stored foods. Gamma radiation has greater penetrating power than electrons and is therefore more appropriate for irradiating packaged foods. Electron radiation is suitable for irradiating foods on conveyor belts in cereal-processing plants where layers of material do not exceed 1.7–3.4 cm in thickness. Both gamma radiation and accelerated electrons cause immediate sterility in insects, but death may be delayed for 2 or 3 weeks after irradiation depending on the absorbed dose and the susceptibility of the species to radiation.

The ventilation of grain as a means of preserving grain quality in concrete, metal, and wooden bins is widely recognized as a good storage practice. Natural ventilation of the grain surface is accomplished by wind currents that enter the bin through ventilators on the roof and eaves and is a satisfactory method of preserving grain quality in bins with a capacity of less than 25 t. However, forced-ventilation systems that move air through the intergranular spaces of grain are becoming more widely used and are more effective. Forced ventilation is accomplished by a fan fitted to one or more perforated ducts of various designs, depending on the quantity of grain and the dimensions of the bin or silo. The air-flow rate may range from 3 to 30 $m^3/h/t$, depending on the size and speed of the fan, the power output of the motor, and the resistance of the grain to the flow of air. In temperate climates, ventilation devices cool grain below the temperatures at which many storage pests develop and reproduce. Forced ventilation also prevents the formation of moist zones within the bulk, where storage pests congregate and contribute to grain heating.

Various combinations of nitrogen, carbon dioxide, and oxygen have been used successfully in certain countries to control the environmental atmosphere in the intergranular spaces of stored grain. Bins must be relatively air tight to maintain gas concentrations to the levels required for optimum reduction of insect infestations. Because of the high cost of constructing air-tight bins, the method has been used only in countries and situations where insecticides may be difficult to obtain or apply, or where insecticides may be ineffective because of the development of insect resistance to them.

Chemical control

Pesticides are relatively inexpensive and easy to apply. They are relied on extensively and often exclusively, on a routine basis, to control pest populations in grain elevators, flour mills, and feed mills. Without chemicals it would be impossible to meet the sanitary standards required for the production and dispatch of insect-free cereals and cereal products to domestic and export destinations. It is therefore the responsibility of regulatory agencies, reinforced by research findings, to ensure that only those pesticides that can meet the required standards of safety, efficacy, and consumer protection are registered and recommended. However, the users of pesticides must accept the ultimate responsibility for ensuring that the chemicals are handled and applied according to the manufacturer's recommendations.

The chemicals used to control insects in the cereal-grains and cereal-processing industries comprise two classes: contact insecticides and fumigants. Contact insecticides kill insects that contact treated surfaces or air particles. They are generally used against insects that crawl or fly in open spaces or on structural surfaces of grain elevators, flour and feed mills, and warehouses. Certain contact insecticides of low mammalian toxicity may be admixed with stored grain to protect it from insect pests or to control established infestations. Fumigants are gaseous insecticides applied to control insects in grains, processed foods, and buildings that are inaccessible to contact insecticides.

Pest control chemicals may come in direct contact with cereal grains, processed cereals, or surface structures where foods are stored. Such chemicals must therefore be selected to meet certain basic requirements to ensure that food products are not contaminated. The ideal stored-product insecticide or fumigant should be toxic to insects but should have negligible toxicity to humans and other warm-blooded animals when used according to recommendations; it should not form toxic products in foods that are treated; it should be safe, easy, and economical to apply and should not impair food value in any way; and, finally, any chemical residues that do occur as a result of acceptable agricultural practices should not exceed the limits set by national and international regulations. These stringent requirements have eliminated from stored-products use many insecticides that have proven effective for control of insects on growing crops. However, a selected few have met most of the basic requirements of a stored-product insecticide.

Mammalian toxicity of an insecticide, its degradation rate, and the formation of toxic metabolites are important considerations in determining whether an insecticide may be used to control stored-product insects. Insecticides are usually tested on rats, mice, and rabbits to determine their toxicity. Toxicity is often referred to as acute, chronic, and dermal. Acute toxicity is poisoning that an animal experiences after exposure to a single dose of a chemical. Chronic toxicity is poisoning that results from repeated doses of chemical over a period of time, which has a cumulative effect and leads to illness or death. Both acute and chronic toxicity result when a toxicant enters the body by ingestion, respiration, or through the skin or cuticle. Dermal toxicity is poisoning by toxicant absorption through the skin, resulting in the production of toxic symptoms.

Mammalian toxicity is determined by the symptoms resulting from exposure of laboratory animals to a graded series of doses of insecticide. These may cause death, paralysis, or injury to the animal. The median lethal dose (LD_{50}) is the amount of toxicant needed to kill 50% of the animals that are treated. The toxicant may be present in the diet or it may be applied on the skin of the animal. The amount of toxicant is usually expressed as the weight of the chemical in milligrams per unit of body weight of the test animal stated in kilograms.

The toxicity of insecticides to insects may be stated as values of LD_{50}, LD_{95}, or LD_{99}. Test insects are exposed to a graded series of insecticide doses applied to various substrates (usually filter paper) or administered to the insect itself. The number of insects knocked down or killed after exposure for a standard time at a stated temperature is used as a response criterion. Insecticides are also tested by bioassay of insects exposed, under experimental conditions, to treated surfaces or to products, or by the assessment of the reduction of natural infestation. Insecticide persistence on treated surfaces is determined by insect bioassay at various times after treatment. Chemical assays of treated surfaces or grain are often used in conjunction with bioassays. The two main classes of insecticides, contact insecticides and fumigants, are discussed separately in this chapter.

Contact insecticides

Contact insecticides kill insects by penetrating the cuticle and disrupting biochemical processes of body tissues; insecticides may also be ingested with treated grain. The insecticide may contact the insect as air-borne particles applied as vapors, aerosols, mists, or sprays. More often, contact insecticides are applied as sprays on structural surfaces to provide residual deposits. Certain insecticide formulations may be used for direct application on grain to protect it from infestation during storage. However, these treatments are used mainly on grain intended for long-term storage on farms.

Contact insecticides are soluble in the oils and fats of plants and animals. Insecticides that penetrate the outer barrier of a plant or insect are transported to various tissues. For example, insecticides can be translocated to the germ and bran portions of treated wheat kernels; very little insecticide accumulates in the endosperm. Lethal effects occur at the sites of biochemical action in various insect tissues and may involve enzymic reactions that affect nervous or respiratory systems. The speed of action will depend on the type of toxicant and the susceptibility of the insect. For example, pyrethrum causes rapid paralysis of insects; however, insects may recover if removed from the source before absorbing a lethal dose.

The contact insecticides used to control insects in cereal grains are selected for the following reasons: they are of low toxicity to humans and warm-blooded animals compared with high toxicity to insects; they do not produce taint or odor in foodstuffs when applied properly at recommended rates; they break down into harmless metabolites after the pests have been controlled; they are safe, easy, and economical to use; and they leave no deleterious residues or toxic products in the food that is to be protected.

Organic insecticides came into widespread use following intensive research of synthetic compounds during World War II. The insecticidal properties of DDT (dichlorodiphenyltrichloroethane) and gamma-BHC or gamma-(1,2,3,4,5,6-hexachlorocychlohexane) were determined in the 1940s, and the use of these insecticides, especially DDT, expanded rapidly in the post-war years. The spectacular success of DDT in stemming the outbreak of louse-borne typhus in Naples in 1944 is well known. Other successes in controlling pests of agricultural crops were demonstrated by substantial increases in the production of food and fiber. It was soon realized, however, that the decimation of crop pests by insecticides created unforeseen problems relating to the environment and human health. In addition, insecticide misuse resulted in the occurrence of persistent chemical residues in soil, animals, and plants. Extensive and intensive use of insecticides also contributed to the development of insecticide resistance in many strains of insects.

Assessment of organic insecticides against stored-product insects began in Canada in 1946. The main classes evaluated were the organochlorine and organophosphorous compounds, and pyrethrum and pyrethroids.

Organochlorine compounds

Although DDT and lindane (99% gamma-BHC) were successfully field tested from 1946 to 1949 to control insects in flour storage warehouses in the Prairie Provinces, neither of these insecticides is currently registered or recommended for controlling stored-product pests in Canada because of possible residues that may occur in stored foods. Both are used, however, in certain countries with warm climates where insects cause serious losses of stored cereals.

DDT. DDT is probably the most universally known insecticide. It may be known by various trade names: Gesarol, Guesarol, Neocid, Neocidol, pentachlorin, Sillortox, chlorophenothene, Accotox, Anofex. Although technical DDT is a mixture of several different isomers, the para, para isomer is the most insecticidally active. DDT contains from 65 to 80% p,p'-DDT, depending on the degree of purity. DDT is formulated as a wettable powder, dust, aerosol, or emulsifiable concentrate. It is persistent when applied to wood or metal surfaces but is less so on porous surfaces such as concrete.

DDT exerts its toxic effects on insects by destroying cellular components that transmit nerve impulses. The acute oral LD_{50} for male and female rats is 113 mg/kg and 118 mg/kg, respectively. The acute dermal LD_{50} for female rats is 2510 mg/kg. DDT is stored in body fat and excreted in milk; it should not be used on or near food.

DDT controls a wide range of stored-product insects; however, it is ineffective against Indianmeal moth larvae (*Plodia interpunctella*). Resistance to DDT has been reported in strains of *Tribolium confusum* in Canada and Europe, and in strains of *Sitophilus* spp. in India, Australia, and Britain. DDT is still used mainly as a residual spray on structural surfaces of grain bins in countries with warm climates. It has also been used as a 25% dust applied as a tracking powder to control mice. DDT is not registered for insecticidal use in Canada because of possible adverse environmental effects. Other less hazardous insecticides are available for control of stored-product insects.

Lindane. Lindane was widely used throughout the world for the control of stored-product insects following its discovery in the early 1940s. It is not registered for the control of stored-product insects in Canada. Other names are gamma-BHC or HCH. Lindane contains 99% of the gamma isomer of HCH. It is stable when exposed to light, air, and carbon dioxide. Lindane breaks down on alkaline surfaces but is persistent on wood surfaces and on stored grains. It is effective as a contact insecticide or stomach poison against a wide range of stored-product insects. Its vapors are also toxic to insects. It may be absorbed by stored flour, to which it may impart a strong musty odor. Lindane may be formulated as an emulsifiable concentrate, wettable powder, or dust. It may also be used in thermal dispensers that produce either insecticidal vapor or smoke to control insects in warehouses or empty ships' holds. The acute oral LD_{50} for male or female rats is 88 mg/kg. The acute dermal LD_{50} for male rats is 1000 mg/kg. Lindane should not be used in contact with stored milled cereals. It is poisonous to fish and honey bees.

Lindane is more effective than DDT for control of stored-product insects but it is less persistent. It has been used successfully for the treatment of interior structural surfaces of flour warehouses. In some countries lindane has been used as a protectant for preventing infestations of stored seed. The occurrence of insect resistance to lindane in certain regions has limited its role as an insecticide.

Organophosphorous compounds

Organophosphorous compounds represent the most versatile group of insecticides used to control stored-product insects. They are used throughout the world as grain protectants and for the prophylactic treatment of grain-storage bins, cereal-processing plants, and grain-handling premises. They are characterized by possessing one or more phosphorus atoms. Although organophosphorous (OP) compounds were developed in Germany as potential nerve gases during World War II, their insecticidal and acaricidal properties were also recognized. Developmental research and the screening of thousands of OP compounds were intensified following recognition of the undesirable persistence of organochlorine insecticides. The OP compounds exert their toxic effects by interfering with the enzyme or enzymes that mediate the transmission of nerve impulses in insects and mammals. Only those OP compounds that are selectively more toxic to insects than to mammals are used for insect control in stored grain or storage premises. Some OPs are relatively nonpersistent and break down into harmless metabolites after they have controlled the target pest species. In that respect they approach the requirement of the ideal stored-product insecticide.

Malathion. Malathion is one of the most important stored-product insecticides ever developed. It has been used widely throughout the world for the past 25 years, although problems of insect resistance have reduced its effectiveness in certain regions. Its low toxicity to mammals (acute oral LD_{50} for rats is 2800 mg/kg; acute dermal LD_{50} for rabbits is 4100 mg/kg) is an advantage in reducing hazards of handling and application. However, extreme caution is still required in its use, despite its low mammalian toxicity.

The chemical name of malathion is *0,0*-dimethyl *S*-(1,2-dicarbethoxyethyl) phosphorodithioate. It is also known as Cythion, Carbophos, Kypfos, and Malaspray. Technical grade malathion is a clear to amber liquid with a garlic-like odor. Certain formulations (e.g., Cythion) do not have much of the unpleasant odor associated with technical grade malathion and have been formulated as a liquid or powder to permit direct admixture with grain. The international tolerance accepted by the Codex Alimentarius Commission of the FAO for malathion residues in cereal grains is 8 ppm. Malathion is formulated as an emulsifiable concentrate (25–86%), wettable powder (25% or 50%), or dust (4%). The emulsifiable concentrate may be impregnated in a substrate of low-grade flour for use as a grain protectant (usually 0.5% or 1.0% active ingredient). Residual persistence in stored grain (e.g., wheat) decreases when the moisture content exceeds 14%. In grain of less than 14% moisture content, malathion at 8 ppm may provide protection from insect infestation for 6 months. Deposits of malathion on wood or metal surfaces have remained insecticidally active for a year under field conditions in Manitoba. When applied on concrete floors at 1 g/m^2, malathion breaks down after about 4 days. Malathion may be absorbed by cereals or oilseeds stored in contact with treated surfaces. However, residues are greatly reduced through admixture when treated grain is transferred to another bin.

Bromophos. Bromophos is effective against a wide range of stored-product insects. A temporary registration was approved for its use in Canada as a spray for grain storage bins, but its use as a stored-grain insecticide was discontinued because of bromophos residues found in stored grain in contact with treated granary surfaces. The acute oral LD_{50} for rats is 4000 mg/kg. The acute dermal toxicity for rabbits is 720 mg/kg.

The chemical name of bromophos is *0*-(4-bromo-2,5-dichlorophenyl)-*0,0*-dimethyl phosphorothioate. It is also known as Nexion and Cela S-1942. It is available as 25% and 40% emulsifiable concentrates, 25% wettable powder, and 2–5% dusts. When bromophos is applied as a spray to concrete surfaces (bromophos as an active ingredient at a rate of 1 g/m^2) it is more persistent than malathion but is slower acting against insects exposed on treated surfaces. Bromophos is effective against some strains of *Tribolium castaneum* that are resistant to malathion. It is therefore one of the insecticides used in countries where malathion resistance has caused problems.

Dichlorvos. Dichlorvos acts as a contact and stomach insecticide, but because of its high vapor pressure (4.28 kilopascals at 20°C) it also acts as a space fumigant. It cannot be relied upon by itself to penetrate stored grain, although studies in Great Britain indicate that when mixed with a carrier gas such as carbon tetrachloride, dichlorvos can be forced through grain by air pressure. It has been used successfully for the disinfestation of empty ships' holds, tightly sealed warehouses, and railway boxcars or containers. Dichlorvos is effective against a wide range of stored-product beetles and moths. For rats, acute oral LD_{50} is 56–80 mg/kg and acute dermal toxicity is 75 mg/kg. Its high acute toxicity suggests that it should be used with extreme caution.

The chemical name of dichlorvos is 2,2-dichlorovinyl dimethylphosphate. Dichlorvos is also known as DDVP, Vapona, Nuvan, and Mafu. It is formulated as emulsifiable concentrates with the use of active ingredient at a rate of 50 and 100 g/100 L, 0.4–1.0% aerosols, and 0.50% granules; a Vapona-20EC pest strip contains 19.2% dichlorvos plus 0.8% related a.i. in plastic.

Dichlorvos formulated in resin strips produces insecticidal vapors for several weeks. When the strips are used in sealed rooms, the vapors produced are effective against a wide range of insects in exposed locations. Good control of moths and beetles was obtained in a flour mill containing an automatic dispenser set to discharge dichlorvos as an active ingredient at a rate of 0.014 g/m^3. Dichlorvos applied in a ship's hold from a vapor dispenser or aerosol cylinder was effective against insects at 40–147 μg/L for 5.5 hours at 22–27°C. Foodstuffs should be covered with tarpaulins during application. Protective clothing and appropriate respirators must be worn during handling and application of aerosols or sprays. Dichlorvos is rapidly metabolized to harmless phosphates in mammals, following exposure.

Iodofenphos. Iodofenphos is not registered in Canada for control of stored-product insects, but because of its effectiveness, low mammalian toxicity, and persistence on structural surfaces, it may be considered an alternative to malathion for control of insects and mites. It is effective against a malathion-resistant strain of *Tribolium castaneum*. For rats, the acute oral LD_{50} is 2100 mg/kg. The chemical name of iodofenphos is *0,0*-dimethyl-*0*-(2,5-dichloro-4-iodophenyl) phosphorothioate. Other names are jodfenphos, Nuvanol N, and the code number C 9491. It is formulated as 20% emulsifiable concentrate, 50% wettable powder, and 5% dust.

Iodofenphos applied to wood surfaces at 0.5 g/m^2 persisted for 16 weeks against five species of stored grain pests. It is slower acting than malathion, but higher doses up to 2.5 g/m^2 prolonged insecticidal activity and accelerated death. It was effective for 12 weeks as a grain protectant insecticide at 10 mg/kg in wheat at 16% moisture content. Malathion breaks down more rapidly at the same moisture content.

Fenitrothion. Fenitrothion is an effective stored-product insecticide but is not registered for control of stored-product insects in Canada. It has a higher mammalian toxicity than malathion. For rats, the acute oral LD_{50} is 800 mg/kg and the acute dermal LD_{50} is 1300 mg/kg. The chemical name of fenitrothion is *0,0*-

dimethyl-*0*-(3-methyl-4-nitrophenyl) phosphorothioate. Other names are Sumithion, Folithion, Novathion, Accothion, and Agrothion. It is formulated as 50% emulsifiable concentrate, 40% and 15% wettable powders, and 5%, 3%, and 2% dusts. It is effective against stored-product insects when applied at 0.25 g/m^2. Certain species take longer to die when treated with fenitrothion than they do with malathion.

Pirimiphos-methyl. Pirimiphos-methyl is a fast-acting, persistent insecticide, effective against a wide range of stored-product insects and mites. It may be used to control malathion-resistant strains of insects, and under moist conditions is more persistent as a grain protectant than is malathion. It is not yet registered in Canada for control of stored-product insects. For female rats, the acute oral LD_{50} is 2050 mg/kg, and the acute dermal LD_{50} is 4592 mg/kg. The chemical name is *0*-(2-diethylamino-6-methylpyrimidin-4-yl) *0,0*-dimethyl phosphorothioate. Other names are Actellic, Actellifog, Blex, and Silosan. It is formulated as 25% and 50% emulsifiable concentrates, and 500 and 1000 g/L ultra-low-volume formulations, dusts, aerosols, and smoke generators. Pirimiphos-methyl provided complete mortality of *Tribolium castaneum* adults for 24 weeks on dry (12% moisture content) wheat treated at 4 mg/kg. It was more stable than malathion on wheat at 16% moisture content and was effective against malathion-resistant *T. castaneum*.

Carbamate insecticides

Carbamate insecticides are not widely used to control stored-product insects in grain bins or processing plants, but several of this group have proved effective in controlling household pests. They act on insects in much the same way as do the organophosphorous insecticides.

Propoxur. Propoxur is used in houses and food manufacturing establishments to flush out cockroaches and stored food pests that have become secreted in cracks and crevices. The acute oral LD_{50} for rats is 100–200 mg/kg; the dermal LD_{50} is >500 mg/kg for male rabbits and >5000 mg/kg for male rats. The chemical name is 2-(1-methylethoxy)phenyl methylcarbamate. Other names are Baygon and Aprocarb. It is formulated as an emulsifiable concentrate, wettable powder, and dust. Propoxur provides a rapid knockdown of insects, and deposits may remain effective for several weeks, depending on temperature and the nature of the surface. Foods and food utensils should be covered when sprays or dusts are applied. Propoxur should not be applied to grain bins or machinery used in the processing or manufacturing of foods.

Bendiocarb. Bendiocarb is effective as a residual insecticide against stored-product insects. When tested against *Tribolium castaneum* and applied at 50 mg/m^2 on metal and fir plywood surfaces, Bendiocarb persisted for 4 weeks. The merchant grain beetle, *Oryzaephilus mercator*, was more tolerant of Bendiocarb than was *T. castaneum*. For rats, the acute oral LD_{50} is 40–120 mg/kg and the acute dermal

LD_{50} is >1000 mg/kg. The chemical name is 2,2-dimethyl-1,3-benzodioxol-4-yl-N-methylcarbamate; an alternative name is 2,3-isopropylidenedioxyphenyl methylcarbamate. Other names are Ficam, Garvox, Multamat, Niomil, Seedox, and Tattoo. It is formulated as a 76% wettable powder, 1% dust, and 25% oil suspension for ultra-low-volume application. It is used mainly by professional pest control operators to control insects in houses and food storages. Special precautions should be followed to ensure that foodstuffs, utensils, and food handling equipment are covered to prevent contamination.

Pyrethrum and pyrethroids

Pyrethrum. Pyrethrum is a botanical insecticide that was used widely before the advent of the post World War II synthetic insecticides. The insecticidal ingredients, known as pyrethrins, form the basis of several hundred formulations of contact insecticides used to control insect pests of stored grain, food storage warehouses, houses, gardens, and animals. Pyrethrin-based insecticides produce rapid knockdown and paralysis of many species of insect pests. Because the insecticides break down rapidly in sunlight and on certain types of surfaces, they were replaced by synthetic compounds, which were developed in the 1940s and which are more persistent. It was eventually realized, however, that insecticidal persistence resulted in undesirable residues in foods, plants, and animal tissues. There has been a trend, therefore, toward greater use of less persistent insecticides, such as pyrethrins, or related synthetic compounds, known as pyrethroids.

Pyrethrins are extracts from flowers of the plant *Chrysanthemum cinerariifolium*, grown primarily in Kenya and Ecuador. The dried flowers contain 1–3% pyrethrins. For rats, the acute oral LD_{50} is 1500 mg/kg and the acute dermal LD_{50} is >1800 mg/kg. Pyrethrins (P) are usually combined with synergists such as piperonyl butoxide (PB) in the ratios 1 P:2 PB to 1 P:10 PB. The synergist retards the degradation of the insecticide and enhances its toxicity to insects.

The active principles of pyrethrins are as follows: esters of pyrethrolone and of chrysanthemic acid, and pyrethroic acids, known as pyrethrins I and II; esters of cinerolone and of chrysanthemic, and pyrethroic acids, known as cinerins I and II; jasmoline, and chrysanthemic and pyrethroic acids, known as jasmolin I and II.

Pyrethrins are available in various formulations: emulsifiable concentrates, oil solutions, aerosols, wettable powders, and dusts. When combined with piperonyl butoxide, they are known under a variety of trade names such as Pyrenone or Pybuthrin. Because of their low toxicity to humans and animals, pyrethrins admixed with flour or diluted with water may be used as a grain protectant to prevent infestation of stored grain. Formulations of dusts or emulsions applied to grain to obtain an intended deposit not exceeding 3 mg/kg pyrethrins and 20 mg/kg piperonyl butoxide have been found effective for several weeks or months, depending on the temperature and moisture content of the grain.

Piperonyl butoxide. Piperonyl butoxide (PB) is a synergist that enhances and prolongs the insecticidal action of pyrethrins and pyrethroids against certain species of insects. PB is usually combined with insecticide in the ratios 2 PB:1 to 10

PB:1 by weight, depending on the species to be controlled. The acute oral LD_{50} for rats is >7500 mg/kg. The chemical name is ∝-[2-(2-butoxyethoxy)ethoxy]-4,5-methylenedioxy-2-propyltoluene. Other names are Butacide and Piperonyl Butoxide Technical. PB is formulated, with a toxicant, as emulsions, wettable powders, oil solutions, pressurized sprays, dusts, and paper coatings.

Pyrethroids. Pyrethroids are synthetic compounds developed to resemble or improve upon the insecticidal activity of pyrethrins. Several pyrethroids that follow are effective against stored-product insects.

Permethrin. Permethrin provides rapid knockdown and paralysis of *Tribolium castaneum* and *Cryptolestes ferrugineus*. It has been tested as a residual spray on wood surfaces. The insects must remain in continuous contact with treated surfaces to achieve mortality. Because of its low mammalian toxicity and insecticidal value, it may become widely used as a stored-product insecticide. For rats, the acute oral LD_{50} is >4000 mg/kg and the acute dermal LD_{50} is >4000 mg/kg. The chemical name is 3-(phenoxyphenyl)methyl (±)-*cis,trans*-3-(2,2-dichloroethenyl)-2,2-dimethyl cyclopropanecarboxylate (approximately 60% *trans*, 40% *cis* isomers). Other names are Ambush, Indothrin, Perthrine, and Pounce. It is formulated as emulsifiable concentrates and wettable powders. When applied at 0.2 g/m^2 it provides rapid knockdown of *T. castaneum* following 24-hour exposure for 33 weeks.

Cypermethrin. Cypermethrin is effective against several stored-product insects. It causes rapid knockdown and paralysis of insects exposed to treated surfaces. The acute oral LD_{50} for female rats is 4123 mg/kg (in aqueous suspension) and 1741 mg/kg (in corn oil). The chemical name is ±∝-cyano-3-phenoxybenzyl (±) *cis,trans*-3-(2,2-dichlorovinyl)-2,2-dimethyl cyclopropane carboxylate. Other names are Cymbush, Imperator, and Ripcord. It is formulated as emulsifiable concentrates and wettable powders. Extreme care should be used in handling and applying formulations. Protective clothing, eye shields, and face shields should be worn. Fumes should not be inhaled. Because of these recommended safety precautions, cypermethrin will probably not be used widely as a stored-product insecticide.

Fenvalerate. Fenvalerate is another candidate pyrethroid that is effective against stored-product insects. It persists for several weeks on wood surfaces. For rats, the acute oral LD_{50} is 451 mg/kg (in nonvolatile solvent) and >3200 mg/kg (in aqueous suspension); the acute dermal LD_{50} is 2500 mg/kg. The chemical name is cyano(3-phenoxyphenyl) methyl 4-chloro-∝(1-methylethyl) benzeneacetate or ∝-cyano-3-phenoxybenzyl 2-(4-chlorophenyl)-3-methylbutyrate. Other names are Belmark, Ectrin, and Pydrin. It is formulated as emulsifiable concentrates, dusts, and wettable powders. Protective clothing should be worn when handling and applying fenvalerate.

Resmethrin. Resmethrin is effective against a wide range of pests that infest households, greenhouses, and stored products. It is persistent on various types of surfaces and causes rapid knockdown of insects in continuous contact with deposits. For rats, the acute oral LD_{50} is 4240 mg/kg and for rabbits, the acute dermal LD_{50} is 2500 mg/kg. The chemical name is [(5-(phenylmethyl)-3-furanyl) methyl 2,2-dimethyl-3-(2-methyl-1-propenyl) cyclopropanecarboxylate]. Other names are Benzofuroline, Chrysron, and Synthrin. Resmethrin is formulated as emulsifiable concentrates, base oils, aerosols, and aqueous pressurized sprays. It may be combined with pyrethrins–piperonyl butoxide.

Mineral dusts

Mineral dusts such as silica, kaolin, and diatomaceous earth are used as grain protectants and contact insecticides to control insects in grain and empty buildings. They cause insects to die when the fine dust particles adhere to the insect cuticle and promote the loss of body water through abrasion and molecular displacement of cuticular lipoids. The dusts are virtually nontoxic to mammals, and therefore they overcome most of the objections to chemical insecticides. Mineral dusts are effective against insects at a low relative humidity (<50%) and low grain moisture content (9–13%). At high humidity and grain moisture content, and in the presence of ground-up grain, insects can apparently compensate for the desiccative effects of the dusts. An important disadvantage of mineral dusts, when admixed with stored grain, is that they adversely affect the handling characteristics and "feel" of the grain. Their use in certain countries, including Canada, is therefore restricted to the protection of small bulks of seed grain that are excluded from commercial marketing channels. When used to treat empty buildings, mineral dusts remain effective for several months provided that they are not removed by wind or air currents or diluted with flour or grain dusts. Tests have shown that paper food containers or adhesive papers impregnated with dusts remain effective against stored-product insects for several months. Dusts blown into the cracks of buildings, grain bins, and kitchen cupboards are effective against stored-product insects.

Several mineral dusts are available as commercial formulations. These are Silica Aerogel, Dri-Die (Silica Aerogel with ammonium fluosilicate), Drione (amorphous silica gel and pyrethrins plus piperonyl butoxide), and diatomaceous earth (also known as diatomite, infusorial earth, and kieselguhr).

Although mineral dusts are stated to be virtually nontoxic to mammals, dust particles should not be inhaled during mixing, handling, or application. A protective dust mask should be worn.

Fumigants

Fumigants are toxic gases formed from chemical compounds applied as liquids, solids, or gases to cereals and cereal products or in enclosed spaces. Fumigants are used to control pests that have penetrated stored grain, flour, or internal building cracks and crevices that are inaccessible to treatment by other pest control agents. Because fumigants are poisonous to humans, protective clothing and a gas mask fitted with the appropriate canister must be worn to provide protection during handling and application.

Safeguards similar to those described for contact insecticides must be followed before fumigants are approved for commercial use. Provided a fumigant meets the required standards of effectiveness against insects, it must be assessed to determine whether it imparts any harmful residues or by-products to materials. Cereal foods destined for domestic consumption or international trade must not contain fumigant residues that exceed tolerance levels established by national agencies. The residues may comprise products of organic or inorganic breakdown that may affect the health of humans or farm animals that consume fumigated products. Continuing reviews of fumigants are carried out by national and international experts to determine whether new toxicological data may invalidate recommendations. Fumigants may react with cereals to form odors, taints, or poisonous residues; they may also react with metal containers, machinery, or electrical fittings. Certain fumigants must be formulated to eliminate the risk of fire and explosion. Precautions should be followed to ensure that fumigants are handled and applied in such a way as to minimize risk to those who apply them, to foods or buildings that are fumigated, and to people who enter premises after the required fumigation period or who handle fumigated products.

Fumigants are used to control insects in the following: grain stored in farm granaries, primary elevators, terminal elevators, and the holds of cargo ships; grain and grain products in flour or feed mills; milling machinery; and flour warehouses or storages that can be properly sealed to confine fumigant vapors for the time needed to control infestations.

The dosage selected for each type of fumigation will depend on temperature of the commodity as well as ambient or outside air temperature; airtightness of the building, bin, or enclosed space; and sorption properties of the material being fumigated. Sorption is a function of the material and of its porosity, moisture content, and temperature. Dosages must be increased when grain is fumigated at low temperatures, high moisture content, or in non-airtight bins. High winds create negative air pressures in buildings, especially on the leeward side, resulting in the escape of gas and decreased effectiveness.

Several fumigants are used widely in Canada and throughout the world; a brief description of the more widely used fumigants is included as follows.

Methyl bromide Methyl bromide (MB) is widely used as a space fumigant to control insects in flour mills, ships' holds, railway cars, warehouses, empty grain bins, and stacks of stored products enclosed in gas-tight tarpaulins. It is also used to fumigate stored grain. When formulated with ethylene dibromide (EDB) in the proportions 30 MB:70 EDB, by weight, it may be used as a spot-fumigant to control infestations in flour milling machinery and stored grain.

Methyl bromide is toxic to a wide range of stored-product insects; it is not flammable and can penetrate rapidly into granular materials. MB has a high specific gravity (3.27 at 0°C) and a boiling point of 3.6°C. Unlike many fumigants, the gas is odorless, and therefore special precautions must be taken during application to avoid inhaling the vapors. Enclosed spaces that have been fumigated must be well ventilated, and gas concentrations must be reduced to zero before people are allowed to enter the premises. The high toxicity of MB to humans makes it imperative that this fumigant be applied only by people who have been trained and licensed to use it. For rats, the acute vapor toxicity is 21 mg/L. The safe upper limit for humans is 0.5 mg/L. Gas masks must be worn at higher concentrations. Vapors can be detected with a halide leak detector consisting of a cylinder of acetylene or other similar fuel and a piece of copper plate or wire heated by the flame. The color of the flame varies with the concentration of gas. Detector tubes and thermal conductivity analyzers may also be used to measure gas concentrations.

The chemical name of MB is bromomethane. Other names are Brom-O-Gas, Celfume, Dawson 100, Dowfume, MeBr, Meth-O-Gas, and Pestmaster. Methyl bromide is contained in glass ampoules (up to 50 mL), pressurized metal cans, and steel cylinders. Small amounts (up to 2%) of the fumigant chloropicrin may be added to MB to act as a warning gas.

Containers of MB should be stored in a cool, well-ventilated area used for the storage of hazardous chemicals. Foods must not be placed near these chemicals either in storage or during transportation.

Methyl bromide is usually applied as a gas, through metal or plastic tubing, to food commodities that have been enclosed in a gas-proof room or a plastic covering. If a large space such as a ship's hold, warehouse, or flour mill is to be fumigated, electric fans must be used to circulate the gas to prevent it from settling in a layer near the bottom of the fumigated spaces.

Dosage schedules vary according to temperature, material to be fumigated, airtightness of the enclosure, and susceptibility of the pest species. Dosages may be increased from outside the fumigated space during the course of a fumigation to maintain the required concentration. Fumigant dosages for bagged cereal grains range from 40 g/m^3 for 16–24 hours at 4–9°C, to 16 g/m^3 for 16–24 hours at >21°C. Processed cereals in permeable packages require dosages that are about 20% higher. Fumigated insects may take several hours or as long as 2 or 3 days to die, depending on the temperature, the susceptibility of the species, and the stage of development.

Ethylene dibromide Ethylene dibromide (EDB) is strongly sorbed on cereals and cereal products and consequently is seldom used alone as a fumigant. Its toxicity to insects is similar to that of methyl bromide. However, it is more toxic to humans, and high concentrations can cause lung irritation and liver and kidney damage. It has a strong odor, and mixtures of EDB and methyl bromide are readily detectable. When mixed with other fumigants that serve as carrier gases, EDB acts as a major toxicant for control of insects in grain stored in farm bins, flour mills, and feed mills. It has also been used as a rodenticide to control rats in burrows. For male rats, the acute oral LD_{50} of EDB is 146 mg/kg; acute vapor toxicity is 200 mg/kg. Acute burning results when EDB is applied to the skin.

The chemical name for ethylene dibromide is 1,2-dibromoethane. Other names, which usually refer to proprietary fumigant mixtures, are Bromofume, Celmide, Dowfume W-85, Dowfume W-90, Dowfume W-100, and EDB-85. Its odor is similar to that of chloroform.

Extreme caution should be followed when handling, storing, or transporting EDB or its various formulations. It should not be stored near food or in buildings that house farm animals. Because of its corrosive properties, EDB may cause leaks in containers. It is widely used as a spot-fumigant in flour mills. EDB may break down to form ethylene glycol, which in turn may react with methionine in wheat protein. Animal feeds that have been fumigated with EDB should not be fed to poultry.

Ethylene dichloride Ethylene dichloride (EDC) is used in admixture with a carrier fumigant, usually carbon tetrachloride (CT), for control of insects in stored grain or flour mills. The fumigant mixture is easy to apply because the liquid rapidly volatilizes and diffuses in grain or flour; EDC has no adverse effect with respect to germination or baking properties of fumigated products. Protective clothing and gas masks should be worn during application, and fumigated premises should be well aerated before they are entered. EDC–CT mixtures (3:1, by volume) are less toxic to insects than are EDB–MB mixtures. For rats, the acute oral LD_{50} of EDC is 670–890 mg/kg.

The chemical name of ethylene dichloride is 1,2-dichloroethane. Other names are EDC, Chlorasol, and Dowfume 75 (the last two are proprietary mixtures containing EDC and carbon tetrachloride). Because of its flammability, EDC must be formulated with carbon tetrachloride or other nonflammable solvent to avoid risk of fire or explosion during application.

EDC has an odor similar to that of chloroform. It is absorbed by whole grains, the extent of absorption being greater at low temperatures. Turning and milling of fumigated grain reduces residues of EDC in milled products; the extent of the reduction depends on initial dosage, temperature, and extent of movement. Food should not be stored near containers of fumigant.

Carbon disulfide Carbon disulfide (CD) is used widely for the control of stored-grain insects. CD is often referred to as carbon bisulfide. Because it is highly flammable, CD is combined with carbon tetrachloride to reduce the fire hazard. The vapor of CD is highly poisonous to humans and produces giddiness and vomiting in 30 minutes after exposure to a concentration of 1:500. The acute vapor toxicity to rats is 200 mg/kg.

Residues of CD in fumigated cereal products are largely eliminated during milling, ventilation, and cooking. CD is not approved for the fumigation of stored beans, peas, or cowpeas. Drums or cans containing CD should be stored in cool, well-ventilated buildings. Extreme care should be taken in handling CD to avoid risk of fire and explosion. Protective clothing and gas masks equipped with appropriate canisters should be worn.

Carbon tetrachloride Carbon tetrachloride (CT) is sometimes used as a fumigant by itself, but because of its low toxicity to insects and the higher quantities required for insect control, it is used mainly in combination with other more toxic fumigants such as ethylene dibromide and ethylene dichloride. CT vapors are very toxic to humans and cause extensive liver damage. For rats, the acute oral LD_{50} is >7500 mg/kg. CT residues in cereals persist in flour even after ventilation, but residues disappear in bread baked from fumigated flour.

Chloropicrin Chloropicrin is one of the most disagreeable fumigants to apply because it acts as a tear gas. It is useful as a warning agent when added to odorless fumigants such as methyl bromide. Chloropicrin is extremely phytotoxic and is also very toxic to insects. It persists in grain at low temperatures, and the vapors are difficult to remove by ventilation. It is toxic to humans and a concentration of 2.4 g/m^3 can cause death from acute pulmonary edema in 1 minute. The acute oral LD_{50} to rats is 250 mg/kg. It is irritating to the skin, eyes, and respiratory tract.

The chemical name is trichloronitromethane. Other names are Acquinite, Chlor-O-Pic, Dojyopicrin, Dolochlor, Larvacide, Pic-Chlor, Picfume, and Tri-clor.

Chloropicrin residues in flour may adversely affect baking quality, although ventilation may remove this effect. Chloropicrin corrodes metal cans and application equipment. Although it is effective, its disagreeable properties prevent its acceptance as a fumigant for the control of insects in stored grain and mills.

Phosphine Phosphine, or hydrogen phosphide (PH_3), is probably one of the most widely used stored-product fumigants. Although by itself it is highly flammable, the formulations that are commercially available completely remove the risk of fire and explosion. Phosphine gas is produced by the action of water vapor on aluminum phosphide, which is combined with a suitable fire retardant such as ammonium carbamate. The reaction causes the release of ammonia, which acts as a warning gas to signal the formation of phosphine, which is highly toxic to humans. A tolerance of 0.1 mg/kg of PH_3 in cereals has been recommended. Phosphine applied at recommended rates to grain does not affect the germination of seeds.

Aluminum phosphide, which releases phosphine, is known by other names assigned by various manufacturers. These are Phostoxin, Celphide, Celphos, Delicia, and Al-Phos. Phosphine has an odor resembling carbide or garlic. Its boiling point is –87.4°C, and the specific gravity of the gas is 1.214 (air = 1).

Commercial formulations are available as 3-g tablets, 0.6-g spherical pellets, or crepe-paper sachets containing 34 g each. The sachets have the advantage of being removable at the end of a fumigation. The tablets, pellets, and sachets liberate phosphine in the amounts of 1 g, 0.2 g, and 11 g, respectively.

Tablets and pellets may be probed into grain bulks or dropped into the grain as it is binned. Pellets are designed for use in automatic applicators. The small amount of aluminum hydroxide powder and unreacted aluminum phosphide that remains after fumigation is dissipated when the grain is turned or cleaned. The sachets containing the aluminum phosphide powders may be dropped into the grain or inserted between bags of grain. They may be extracted from the grain during transfer or removed manually. Expended sachets can be disposed of by burying in an approved isolated location inaccessible to humans and animals.

Tablets are packaged in airtight metal tubes that may contain up to 30 tablets each. Pellets are packaged in metal flasks that contain about 1 kg. Tablets and pellets are coated with paraffin wax to delay reaction with air after application. Sachets are packed in airtight containers.

Phosphine reacts with copper and other metals during fumigation. Precautions may therefore be taken, where feasible, to enclose electrical switches with gas-proof covers in buildings that are fumigated.

The dosages recommended and the duration of fumigation required to control insects in stored grain depend on the type of storage structure and the temperature. Fumigation with phosphine is usually not recommended if the grain temperature is less than about 10°C and the relative humidity is less than 25% (equivalent wheat moisture content is about 9%). Dosage schedules may change as more research information becomes available. Current recommendations for fumigation of bulk wheat stored in steel bins at 20°C are 4–6 tablets (20–30 pellets) per tonne for 7 days. The grain should be covered with a plastic tarpaulin to confine the fumigant vapors. If the grain is not covered, the roof of the bin should be made as airtight as possible and the dosage should be increased to allow for fumigation of the headspace. Tarpaulins should not be left in position longer than necessary, because moisture accumulation underneath will heat the grain and subsequently spoil it through microbial activity.

Fumigant mixtures

Many of the fumigants described in this chapter are combined with each other or with other gases such as carbon dioxide to improve effectiveness, reduce the risk of fire or explosion, or provide a warning odor. Formulations of fumigant mixtures are marketed by various commercial firms. Examples of several fumigant mixtures are as follows:

- Carbon disulfide + carbon tetrachloride (16.5:82.5) by volume + 1.0% inert ingredients. The carbon tetrachloride is added to eliminate fire hazard. This mixture is used as a stored-grain fumigant. The dosage usually ranges from 0.5 to 1 L/t.
- Ethylene dibromide + ethylene dichloride + carbon tetrachloride (7:29:64) by volume. The CT is added to eliminate fire hazard from EDC and to improve distribution throughout a grain bulk of the more toxic components EDB and EDC. EDB, because of its strong sorptive properties, tends to remain near the point of application. Dosages range from 0.1 to 1 L/t, depending on grain temperature, moisture content, tightness of storage bin, and grain dockage. Other formulations of EDB + EDC + CT (20:20:60) or EDB + CT (15:85) are used as spot fumigants in flour mills. Dosage schedules, listed on the container labels, range from 140 mL for elevator boots to 280 mL for bran dusters.
- Ethylene dibromide + methyl bromide (70:30) by weight. This mixture is often used as a spot fumigant in flour mills. Because both constituents are very toxic to insects, lower dosages (50 mL for elevator boots) are required to provide control comparable to that provided by higher dosages of EDB + CT mixtures.

  EDB + MB may also be used in the proportion 30 EDB:70 MB as a grain fumigant. The mixture is contained in pressurized cans, each weighing about 454 g. It is suitable for fumigating small lots of grain, e.g. <27 tonnes. The grain surface should be covered with a plastic tarpaulin to retain the vapors. Experimental evidence indicates that EDB + MB mixtures are more toxic than either fumigant alone.

- Methyl bromide + chloropicrin (98:2) by weight. Chloropicrin is used as a warning agent for MB, which is odorless and hazardous to humans. Dosages range from 18 to 30 g/t of wheat at 10–19°C, depending on temperature.
- Ethylene dichloride + carbon tetrachloride (3:1) is a widely used grain fumigant. It has no adverse effect on seed germination. CT eliminates fire hazard and aids in the distribution of gases throughout the grain bulk. Dosages range from 0.5 to 1.0 L/t of wheat, depending on temperature, type of storage bin, grain moisture content, and dockage.
- Carbon dioxide has been used with methyl bromide or phosphine to improve fumigant distribution and toxicity. The demonstrated combined action of carbon dioxide with either of these fumigants holds promise for practical exploitation in the future.
- Methyl bromide–phosphine mixtures can cause high insect mortality at lower dosages and shorter exposure times than either fumigant used alone.

Pest control management

The availability of a wide range of insect control methods requires that a strategy be developed to ensure that the various methods complement each other in concept, design, and application. Each control method, whether chemical or nonchemical, has its own advantages and limitations. Several controls can often be combined to exploit their advantages and minimize their shortcomings. For example, it is possible to combine the advantages of fumigants that have a short period of effectiveness with insecticide sprays that provide longer residual protection when applied to the interior of storage structures. The use of chemicals should be supplemented by sound sanitation practices in elevators and mills, by the use of insect-proof bags, and by the storage of products in clean, uninfested, cool warehouses. Such a protective system of controls applied in proper sequence should make it virtually impossible for infestations to develop. Finally, the application of any combination of insect control measures should be monitored afterwards for the presence of insects to determine whether treatments have been successful. All too often, token treatments are applied to conform with regulations without adequate follow-up to assess results.

The implementation of an insect-control program requires a thorough appreciation of all the elements of an infestation problem: the insects, their habitats, and the various chemical and nonchemical methods available. This presupposes a knowledge of the biology and ecology of an insect pest species and the stored-product ecosystem of which it is a part. Decisions must be made concerning the most appropriate and feasible nonchemical methods, fumigants, and contact insecticides to be used—when, where, and how to apply them effectively, and the safety precautions required to protect the applicator and the food consumer. These are formidable requirements, but if they are pursued, the benefits will be worthwhile: the assurance of a pest-free product with no undesirable side effects and the confidence that the product to be marketed will satisfy the demands of the consumer.

CHAPTER 6 RESISTANCE OF INSECTS TO INSECTICIDES

A major factor limiting the successful use of chemicals for insect control is the emergence of insect strains that possess the ability to detoxify or counter insecticides. The intensive and widespread use of insecticides is one of the main factors contributing to insecticide resistance. Furthermore, misuse of insecticides and failure to apply them in conjunction with other control measures such as sanitation has intensified the problem. The selection process that favors the survival of strains under adverse circumstances is basic to the nature of all living things. The resistance phenomenon involving genetic inheritance is not completely understood. Some strains of a species may possess the mechanisms required to detoxify an insecticide, whereas other strains of the same species in another geographic or regional location apparently may not possess this ability. Alternative insecticides are sometimes used successfully in controlling resistant strains of insects. Often, however, the detoxifying mechanisms present in the resistant strain enable the insect to survive the effects of the alternative insecticide. This phenomenon is known as cross resistance, and resistant strains may pass on their genetic traits for resistance to succeeding generations. Eventually, the majority of a single-species population in a closed environment such as a warehouse or the cargo hold of a ship may become extremely resistant to one or several insecticides used routinely for control of the pest.

Insects have developed resistance to contact insecticides more rapidly and to a greater extent than to fumigants. Perhaps this is because contact insecticides, being less expensive and easier to apply than fumigants, are more widely used. A worldwide survey in 1972 of stored-product insects, sponsored by the Food and Agriculture Organization of the United Nations (FAO), revealed that 87% of 505 strains of the red flour beetle, *T. castaneum*, collected from 78 countries, were resistant to malathion. Resistant strains were found in 75 countries. By 1980 a further eight species of stored-product beetles and moths had developed resistance in the field, and several of these species have also shown resistance to other organophosphorous insecticides as well as to synthetic pyrethroids. Recent information (C.E. Dyte, Britain 1983, personal communication) on resistance to malathion, phosphine, and methyl bromide in North America and elsewhere is given in Table 2. In several countries where malathion resistance is a severe and widespread problem, other control methods that use alternative insecticides, fumigants, or physical control methods have had to be substituted. These alternative measures have added substantially to the cost of controlling insects.

The transport of infested foods in infested vehicles and ships has undoubtedly contributed to the spread of insecticide-resistant strains throughout the world. The severity of the problem was demonstrated by a survey of insect interceptions from grain cargo ships of foreign registry inspected at Canadian East Coast and West Coast shipping ports during 1973–1975. All 22 strains of the red flour beetle, *T. castaneum*, collected were found to be resistant to malathion. Chemical control treatments of insect populations in ships' holds provide ideal conditions for the selection, survival, and international distribution of insecticide-resistant strains. The application of insecticides to meet sanitary standards imposed by regulatory authorities contributes substantially to the build-up of resistance in confined

Table 2. **Resistance to malathion, phosphine, and methyl bromide in the major insect pests of stored grain in North America and in the world**

Species	Malathion		Phosphine		Methyl bromide	
	North America	World*	North America	World*	North America	World*
Corcyra cephalonica	0†	0	0	0	0	0
Cryptolestes ferrugineus	+‡	+	0	+	0	0
Ephestia cautella	+	+ +§	0	+	0	0
Ephestia elutella	0	0	0	0	0	0
Oryzaephilus mercator	+	+	+	+	+	+
Plodia interpunctella	+ + +‖	+ + +	0	0	0	0
Rhyzopertha dominica	+	+ + +	0	+ +	0	+
Sitophilus granarius	0	+	+	+	0	+
Sitophilus oryzae	0	+ +	0	+	0	0
Sitophilus zeamais	0	+	0	+	0	+
Sitotroga cerealella	0	+	0	0	0	+
Tribolium castaneum	+ + +	+ + +	+	0	0	0
Tribolium confusum	+ +	+ + +	+	+ +	+	+
Trogoderma granarium	0	+	0	+	+	+

- * World records also include those from North America.
- † Resistance not known.
- ‡ Resistance reported.
- § Resistance reported and is a problem in several countries or in several regions of a large country.
- ‖ Resistant strains widely distributed.

populations, unless the effectiveness of the treatment is assessed and steps are initiated to ensure the complete control of surviving insects. Failure to do so may result in the continued survival and transport of insects in ships' holds.

The survival of insects following an insecticide treatment may be the first indication of a resistance problem. Provided that the insecticide has not been improperly applied as a result of inadequate dosage or spraying, the surviving insects may be tested to determine whether they are resistant to one or several insecticides. A method that makes use of treated filter papers has been adopted by FAO as a standard test for detecting resistance in certain stored-product species. Groups of insects are exposed to filter papers treated with an amount of insecticide that is just sufficient to knock down all individuals in a strain known to be susceptible to the insecticide. The strain to be tested is exposed to similarly treated filter papers for 5 hours. Insects that are not knocked down are considered to be resistant. The severity of resistance is proportional to the number of survivors. Where insufficient numbers of survivors have been collected for a test, it may be necessary to start a culture and test the adult progeny.

Among the most obvious consequences of insecticide resistance is the presence of many insect survivors after a treatment. The failure of an insecticide may initiate a chain of events. Infested foods or grain shipments may cause a flow of complaints from customers. The spread of resistant insects on products sent to other destinations will generally intensify the resistance problem. A control failure may be corrected temporarily in certain circumstances by increasing the dosage. However, this practice may not only be more costly but may also increase the risk of exceeding the legal limits of toxicant in a food, contaminating it, and exposing personnel to higher concentrations of insecticide or fumigant during application.

When a problem of insect resistance has been identified, an alternative pest-control method must be applied. Substituting a different insecticide may provide control as long as resistance does not develop again. Insecticide-resistant insects are often controlled with fumigants, which are generally more expensive to apply than contact insecticides. Physical control methods offer an alternative to the use of chemicals. Low temperatures, ventilation, atmospheric gases, and radiation are viable alternatives that are being used increasingly or considered as adjuncts to, or replacements for, chemicals. Physical control methods, however, cost more than chemicals, and require more sophisticated technology.

CHAPTER 7 INSECTICIDE APPLICATION AND SAFETY

Insecticides must reach insects in the form and amount necessary to control them. The choice of an insecticide and its appropriate formulation, dosage, and method of application must be based on a knowledge of the biology of the pest species, the location of infestations, the susceptibility of various stages to the toxicant, and the habitat or food that the insect infests. The overriding considerations in all cases must be effectiveness and human safety. The insecticide, formulation, and method of application must be selected to achieve maximum effectiveness at the lowest feasible dosage, and the insecticide must be handled, dispensed, and applied safely, with minimum risk to the applicator and consumer of the grain or commodity that is to be protected.

This chapter deals with the application of contact insecticides and fumigants and the safety precautions that must be followed.

Contact insecticides

Contact insecticides may be dispensed in air as fine particles or droplets to control flying insects; they may be applied as sprays to the structural surface of granaries, elevators, mills, or warehouses; or certain approved insecticides may be applied directly to stored grain.

Insecticides are formulated as dusts, oil solutions, emulsifiable concentrates, wettable powders, aerosols, or slow-release vapor strips. The selection of a particular formulation will depend on the insect species to be controlled and the type of surface or product it infests. Oil solutions, applied as mists or fogs, are appropriate for controlling flying insects, but are much less effective than wettable powders for treating concrete or other types of masonry surfaces. Certain formulations, such as aerosols, dusts, or powders may be applied directly from the container. Most formulations, however, are in a concentrated form and before application must be diluted with water (for emulsifiable concentrates and wettable powders) or oil (for oil solution concentrates). The usual application rate is 5 L/100 m^2 of structural surface to be treated. The concentration of insecticide required to control an infestation depends on species of insects present, temperature of the surroundings, and type of surface to be treated. Insecticides are usually applied at concentrations that range from 1 to 5%. Application instructions are usually listed on the label of the insecticide container. Dosages vary according to the type of insecticide and the species to be controlled.

The amount of oil or water to be added to a portion of concentrate to obtain a spray fluid can be calculated easily by the following example. A 2% spray can be prepared from a 50% emulsifiable concentrate by adding 24 parts of water $\left(\frac{50\%-2\%}{2\%} = \frac{48}{2} = 24\right)$ to 1 part of concentrate. Therefore, to make up 5 L of 2% spray from a 50% emulsifiable concentrate, add 4.8 L of water to 0.2 L of the 50% concentrate.

When an oil solution with a deodorized kerosene base oil is prepared, it may be necessary to first dissolve the insecticide in an organic solvent to facilitate formation of a solution in the deodorized kerosene. Oil-base insecticides are effective for the treatment of unpainted structural wood surfaces, where they may persist for several months. The spray can be applied near electrical switches and outlets, where water-base insecticides would be hazardous. To control flying insects, oil solutions can also be used in electrical sprayers that produce a fine mist of insecticide particles (0.03–0.1 mm in diameter).

An emulsifiable concentrate consists of a toxicant or toxicants and an emulsifying agent in an organic solvent. The emulsifying agent reduces the tendency of the oil-base toxicant to separate from the solvent. The addition of water to the concentrate results in the formation of a milky emulsion consisting of a suspension of small oily droplets of insecticide. Emulsions may "break" and separate into layers of water and toxicant unless they are agitated in the sprayer during application. Emulsifiable sprays are suitable for treatment of metal and wood surfaces; they are less persistent on porous concrete surfaces. Certain formulations may be used to treat infested grain or to protect uninfested grain from insects during shipment and storage.

Wettable powders are finely ground mineral powders impregnated with insecticide. Wetting agents are incorporated into formulations to lower surface tension and promote suspension of particles when diluted with water. Wettable powder formulations are suitable for treatment of all types of structural surfaces, but they are especially recommended for application to porous surfaces, such as concrete. Wettable powder spray particles may spoil the appearance of painted surfaces by leaving white specks. To facilitate a uniform admixture of powder with water, a water slurry is first prepared by mixing a small amount of water to the required weight of powder. The rest of the water is then added to the slurry. Sprayers must be fitted with coarse spray nozzles to prevent clogging of openings.

Sprayers

Portable pressurized tank sprayers, with capacities of 5–15 L, are widely used to apply oil solutions, water-diluted emulsions, and wettable powder solutions. The openings of nozzles used to discharge oil solutions and emulsions are about 0.4 mm in diameter, whereas those used for wettable powder solutions range from 0.8 to 1.2 mm in diameter. Sprays are applied on the floor and walls, especially at wall and floor junctions, where insects are most often found.

Power sprayers

When large surface areas in warehouses or ships' holds must be treated, power sprayers are usually required. One type, a motorized knapsack sprayer fitted to a frame, straps on the back of an operator. All safety regulations governing the use of sprays and sprayers in buildings, ships, and mills must be followed.

Mists and fogs

Several types of electrical sprayers have been developed for producing insecticidal mists that have a range in particle size of 0.03–0.1 mm in diameter. The small insecticide particles have a short residual activity on most structural surfaces except on horizontally exposed unpainted wood surfaces, where experiments have shown that pyrethrum deposits remain effective against insects for several weeks. Although misting devices can discharge emulsions and wettable powders, they are most commonly used to apply oil solutions. When used for moth control, mists must be applied at 3-day intervals to control emerging adults before they mature, mate, and lay eggs.

Fogs are produced by thermal generators. The liquid droplets are less than 0.03 mm in diameter. In one type, the hot air passes at high velocity through a combustion chamber past a hydraulic sprayer nozzle that emits an oil-base spray into the hot air blast, with the oil solution emerging as fog. Fogs may also be produced by steam formed from an insecticide–oil solution and water pumped through coiled tubing leading into a combustion chamber. Several types of thermal fog generators are available commercially. Insecticide–steam fogs have been used successfully on an experimental basis to control insect infestations of bucket elevator legs in flour mills.

Dusts

Inert mineral dusts are usually applied by hand-held pump guns directed at places that are difficult to treat with sprays. Dusts are effective in dry areas of a building where air drafts will not remove deposits from treated surfaces. The effectiveness of mineral dusts is reduced by admixture with milled cereals or grain dust.

Dust protectants consist of an approved insecticide, such as malathion or pyrethrum, plus a synergist; a low-grade cereal flour or an inert material such as magnesium silicate is impregnated with the protectant. Only flour-based dust protectants may be used to treat cereal grain intended for commercial use. Metered devices are used to apply dust to grain as it is binned. The silica-based dusts are generally restricted to use on seed grain, partly because of the changed flow characteristics of grain so treated. The effectiveness of mineral dusts used for seed treatments is greatly reduced when the moisture content of the grain exceeds that of grain graded as dry (grain with a moisture content in equilibrium with 70% relative humidity).

Smokes and vapors

Certain insecticides such as lindane and dichlorvos have been formulated as smoke generators for the treatment of warehouses and ships' holds. Although effective, they are not available for use in Canada because of possible residue problems in grain debris removed from ships' holds.

Dichlorvos vapors may be emitted by a vapor dispenser that uses a flow of warm air over dichlorvos-impregnated resin pellets or from a steel cylinder that contains dichlorvos, with freon as a propellant. Both methods are found to be effective for the treatment of ships' holds. Dichlorvos vapors are also produced from commercially available resin strips impregnated with insecticide. The rate of release of insecticide vapors from the strips is determined by the temperature and humidity of the surroundings. The strips usually remain insecticidally active for several weeks and are effective for the control of flying insects in warehouses. The vapors do not penetrate into grain sufficiently to be regarded as a gaseous fumigant.

Fumigants

Fumigants are applied as gases, solids, or liquids to control insects in stored grain, bulk or bagged flour, warehouses, and cereal-milling equipment. Application methods vary according to the fumigant that is used and the commodity or structure that is to be fumigated. Because fumigants act against insects in the gaseous state, precautions must be taken to confine the gas so that sufficiently high concentrations are maintained for the time needed to control the insects. Sacked commodities must be tightly enclosed within gas-proof tarpaulins; buildings or ships' holds must be sealed; and bulk grain must be covered with gas-proof sheets. When partly open structures, such as flour-milling machinery, are fumigated, dosages must be increased to compensate for gas leakage.

Dosage rates are listed on the container label by the fumigant manufacturer or distributor. The rates vary according to the commodity or building temperature, the extent to which the commodity may absorb the gas, the size and shape of the enclosure to be fumigated, and the possible rate at which the gas might leak from the structure or commodity. The main consideration in calculating dosage is to estimate how long the gas concentrations will remain high enough in the enclosed space to control the insects that are present. Some species of insects are more susceptible to fumigants than others; and there are differences in susceptibility between insect stages. The fumigant dosage chosen is therefore based on its performance against the species and stages that are most difficult to control; this in turn ensures control of the more susceptible species and stages.

Small bulks of grain

Small quantities of grain (less than about 100 t in small silos) can be fumigated with aluminum phosphide tablets or pellets, or liquid fumigants. Prior to fumigation, the granary is sealed as tightly as possible with a caulking compound or cloth tape to prevent gas leakage. The grain surface must be relatively level. The tablets or pellets are applied through metal tubes about 5 cm in diameter and 1.5–2.5 m long. To provide uniform coverage, tubes are inserted over the grain surface at intervals of 1 m^2, and then tablets are dropped down the tubes as they are withdrawn from the grain to ensure even distribution at each location. After treatment, the grain surface is covered with a gas-proof sheet to confine the fumigant vapors.

Liquid fumigants should be applied only from an open door or hatch. Application of fumigants inside buildings is not advisable because the high concentrations that develop may not be removed by ordinary gas mask canisters. Liquid fumigants may be applied with a stirrup pump fitted into a covered drum containing the fumigant. A flexible hose terminating in a coarse spray nozzle attachment is used to spray the fumigant over the grain surface. Two persons, each wearing gas masks, are required.

Large bulks of grain

Larger quantities of bulk grain in flat storage buildings about 10 m high or stacks of grain covered with gas-proof tarpaulins may be treated with aluminum phosphide pellets or tablets or with methyl bromide (MB) applied through plastic tubing from steel cylinders. The grain surface must first be leveled, and after application of the fumigant it must be covered with plastic sheeting that is sealed at the edges to confine the vapors. The gas formed by vaporization of liquid MB (boiling point, 3.6°C) is released through perforated metal pipes into the enclosed space above the grain. Moisture from the grain may condense on the inner surface of the plastic cover if it is left in place for longer than a day.

Certain terminal elevators have special silos that are modified for grain fumigation. The silos are fitted with pipes and air circulation systems that distribute and retain the gas for the time required to control an infestation.

Equipment is available for dispensing aluminum phosphide pellets into grain as it is augered into bins. Aluminum phosphide formulations are also available in sachets that weigh 33 g and produce 11 g of phosphine (PH_3) when exposed to air.

Stored grain may be infested in localized regions of a grain bulk, at or below the grain surface. Such regions may become heated as a result of insect and microbial activity. The rest of the grain may be cool and relatively uninfested. Treatment of the infested parts may be all that is required to keep the grain in good storage condition during cool weather. The infested parts may be fumigated directly by applying liquid fumigant through metal pipes perforated at the bottom. The bottom of the pipe is inserted at various locations below, around, and inside the infested zone. The grain may also be fumigated with aluminum phosphide tablets or pellets that are dropped down a 5-cm diameter pipe inserted below, around, and within the infested zone. Phosphine takes longer (3–7 days) to control insects than do most liquid fumigants.

Flour mills

In flour mills and other cereal-processing plants, fumigants have an important role for the control of insects that have become established in milling equipment and in areas that are not accessible to treatment with contact insecticides. The specialized equipment used in the milling industry, such as cleaners, roll stands, separators, sifters, conveyors, and storage bins, provides food and protected environmental conditions where insects can breed and multiply. The high, open spaces and interior structures of mills provide places for moths and beetles to live, move, and reproduce.

Space fumigation

Fumigation of the open spaces of a mill and of milling equipment may be accomplished with MB, hydrogen cyanide, mixtures of MB and ethylene dibromide (EDB) (70% MB + 30% EDB), and phosphine. In certain circumstances dichlorvos may be used. The suppliers of fumigants provide complete instructions for applying each type of fumigant. All fumigants used for space fumigation, except phosphine, are usually supplied in steel cylinders of various sizes, which may be placed at several positions on each floor of a mill or connected to a system of pipes inside or outside the mill. Before it is released in the mill, MB may have to be vaporized by passing the liquid through coils immersed in hot water.

Electric fans on each floor help to distribute fumigant vapors that would otherwise tend to stratify in accordance with their specific gravity. Cylinders on the top floor are opened first, followed quickly by those on successive lower floors. Aluminum phosphide tablets are placed on thick paper and distributed throughout each floor.

Before the start of a space fumigation, all equipment should be emptied of cereal stock and opened to permit penetration of fumigant gas. Badly infested and spoiled material should be fumigated in an airtight fumigation vault and then buried in a refuse pit. Windows, doors, and ventilator openings should be closed securely and sealed.

The duration required for a space fumigation depends on the type of fumigant used. Fumigants such as hydrogen cyanide act quickly, and space fumigations can be accomplished in 12 hours or less. MB fumigations can be done in 24 hours. However, phosphine acts much slower on insects and requires 2 days or longer.

Spot fumigation

The direct fumigation of milling machinery, when the mill is closed down, usually during a weekend, is relied on extensively to control infestations and thereby maintain the sanitary standards of the mill operation. Various formulations and dosages may be applied to milling equipment. Automatic applicators may be placed at central locations and adjusted to deliver a preset dosage when inserted into milling equipment. Ductwork and outlets may be installed in mills to facilitate application of spot fumigants to milling equipment. Operators must work in pairs, must be equipped with suitable protective clothing, and must wear gas masks. Equipment on the bottom floor should be fumigated first, followed by fumigation of the second and subsequent floors to avoid working in high concentrations of heavy gas vapors. All fumigated buildings must be posted with warning signs. Guards must be posted to enforce security until after the building has been fumigated and ventilated, and the premises have been declared free of gas.

Fumigation vaults

Specially constructed gastight rooms or chambers are used to fumigate infested sacks and cereal products at controlled temperatures, pressures, and gas concentrations. If it is necessary to fumigate at lower than atmospheric pressure, chambers must be designed to withstand the required stress. All fumigation vaults must be equipped to introduce, distribute, and remove fumigant gases safely and effectively. The design, construction, and operation of a fumigation vault must conform to regulations and local ordinances.

Factors affecting fumigation

Insects must be exposed to fumigant gas at a sufficient concentration for an adequate period of time to give control. Environmental temperature influences the effectiveness of fumigants on insects. Insect adults and larvae are most active at 25–35°C, and fumigations are therefore most effective within this range. Fumigation is generally not recommended below 10°C because of the possibility of ineffective insect control and the high sorption of fumigant by the commodity. Sorption is a complex phenomenon in which gas can be taken up chemically or physically by a material. Sorption of gas is influenced by the temperature and moisture content of the material; some cereals and milled products sorb more fumigant than others.

Temperature differences within grain can cause convection air currents that influence the diffusion and distribution of fumigant vapors. It is therefore necessary to apply fumigants as uniformly as possible to ensure an even distribution of gas. Low temperatures at the periphery of a grain bulk and higher temperatures near the center influence the downward and upward movement of fumigant vapors. Gas leakage from structures and wind currents may also affect gas distribution.

Safety

Safety in handling and applying pest control chemicals is of paramount importance. Regulatory agencies are primarily responsible for the approval of safety recommendations. All chemicals proposed for the control of stored-product insects are subject to scrutiny on the basis of their technical specifications, safety of use, and claims for efficacy. Pest control chemicals that meet the required criteria may be registered for a stated use. The Pesticides Division of the Food Production and Inspection Branch of Agriculture Canada is responsible for the scrutiny and registration of pesticides.

Stored-product insecticides must meet special requirements before they are approved for use. Insecticides must not contaminate or taint products with which they may come in contact; they must have a low mammalian toxicity to safeguard both those who apply them and consumers of treated foods; residues of insecticides or fumigants found on grain as a result of recommended practices must not exceed specified tolerance levels; they must be effective under stated conditions of use; and they must not pose health hazards. These requirements limit the number and kinds of chemicals that are available for control of stored-product insects.

All pesticides must be used in accordance with the manufacturers' recommendations, usually stated on the container label. Doses and safety precautions are clearly stated to protect the operator and to ensure that the insecticide is applied in the manner needed to obtain maximum effectiveness.

Contact insecticides

Contact insecticides are usually supplied as concentrates that must be diluted to the required concentrations with oil or water. Care must be taken during mixing to protect the hands and face from contact with the insecticide. Neoprene or rubber gloves and rubber boots must be worn, whereas leather or cloth gloves must not be worn. Eyes must be protected with safety glasses, and gas masks with suitable canisters must be worn to prevent inhalation of harmful vapors. Suitable garments must be worn to protect clothing. After spraying, equipment should be drained and rinsed with water. Spray droplets, gloves, and clothing should be washed off with water, and hands and face washed thoroughly.

Sprayers and protective clothing should be stored in a safe, well-ventilated room that is locked to prevent unauthorized use. Chemicals in containers should be stored on shelves in a separate room equipped with benches, sinks, and a supply of hot and cold running water. The room should be ventilated to prevent accumulation of noxious fumes.

Empty containers should be washed thoroughly with water, punctured to prevent their reuse, and then buried in an approved refuse pit. The water used to wash insecticide containers should be disposed of in accordance with local regulations. One method is to distribute it over gravel drainage areas subject to weathering and protected by a fence.

Dust masks, safety glasses, and gloves must be worn when applying mineral dusts. A dust gun is usually used, and application is usually started in locations farthest from the door.

Fumigants

It is essential to wear a full-face gas mask (preferably a positive-pressure type) when handling, dispensing, or applying fumigants. A suitable canister must be fitted to the gas mask. One type of canister does not necessarily provide protection against all types of fumigant gases; some canisters are specific against only one type of gas. The fumigant manufacturers recommend the type of canister to be used, and these recommendations should be scrupulously followed. Canisters have a specified shelf life that should not be exceeded. They should be replaced after each period of use. Gas masks should be washed and dried thoroughly after being used, and they should be tested for tightness before the wearer enters a room or area under fumigation. Protective clothing and rubber gloves must be worn, and clothing that comes in contact with spilled fumigant must be removed immediately. At least two persons should be present when applying a fumigant. After a fumigant application, doors should be nailed or locked and warning signs posted.

Part II

Canada

CHAPTER 8 CANADIAN GRAIN-STORAGE SYSTEM

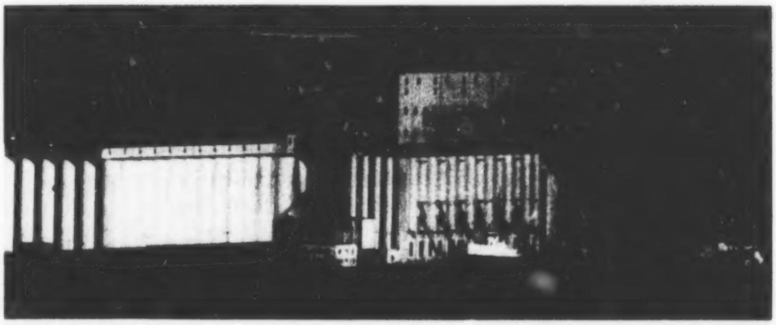
Canadian grain moves from farms to markets in a series of stages. Each stage represents a link in the storage–distribution–processing–marketing network. Various factors at each link in the network may adversely influence the quality of grain or its products. Insects and other stored-product pests may infest products passing through the system. The damage that insects cause, however, is eliminated or minimized by a series of regulatory procedures and, when necessary, by the prompt application of remedial measures.

The main links in the chain are as follows: primary elevators, some 3000 of which are located in the grain-growing regions of the Prairie Provinces; 19 terminal elevators located at export positions on the West Coast, in Thunder Bay, Ont., and in Churchill, Man. (Fig. 20) and five interior terminals in Alberta and Saskatchewan; 27 transfer elevators located on the Great Lakes–St. Lawrence Seaway System and at export positions on the East Coast; flour mills (Fig. 21); feed mills (Fig. 22) and other cereal-processing plants located in most provinces; and railway cars and ships. All storage- and food-processing facilities are monitored by periodic, regular inspections: railway cars are examined at grain-loading points before they are filled with grain; ships are inspected before they are loaded and, if necessary, remedial action is taken to control infestation.

Agriculture Canada assumes a major role in the inspection and quality control designed to maintain the high standards expected of Canadian grain and grain products both in Canada and abroad. The Canadian Grain Commission has the responsibility for controlling the quality of grain at the first link in the chain, the primary elevator, where grain is received from farmers and grade and quality are first established. All elevators in the system, together with ancillary operations, such as handling, drying, cleaning, and storage, must comply with the standards and regulations required to maintain the quality of products that pass through the elevator. In order to meet the licensing requirements, this includes freedom from pests, because infested grain delivered to primary elevators cannot be accepted for storage until it has been fumigated.

The Pesticides Division of the Food Production and Inspection Branch of Agriculture Canada is responsible for inspecting the following facilities: terminal elevators at export positions; transfer elevators situated on the Great Lakes and the St. Lawrence Seaway shipping system; flour mills and other cereal-processing mills that handle or manufacture products for export; and ships that transport Canadian cereals, oilseeds, and their products to foreign destinations. Each facility constitutes a link in the food chain and, as such, must conform to the rigorous standards established to ensure that Canadian food is handled, manufactured, and transported in facilities that are essentially free of insects and other pests that detract from its appearance and quality. Phytosanitary certificates are issued when the appropriate standards have been met.

The regulatory agencies of Agriculture Canada rely on the Research Branch to provide information on the biology of insects and other organisms that attack stored products, the pest status of these organisms both in Canada and in other countries, and appropriate control recommendations.



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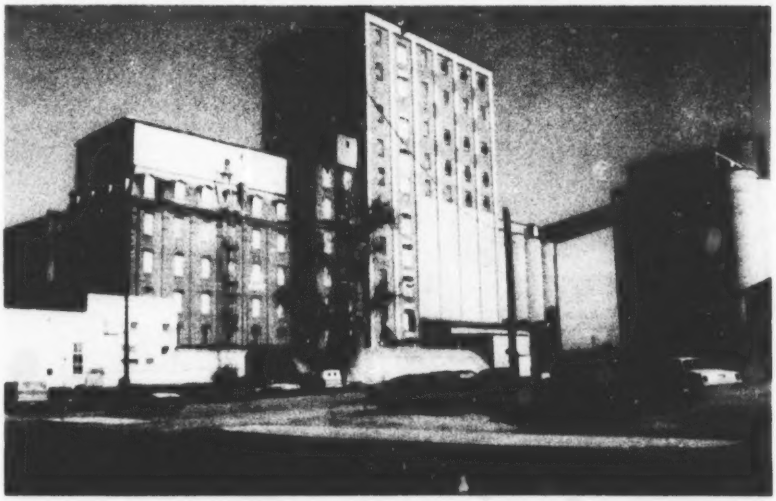

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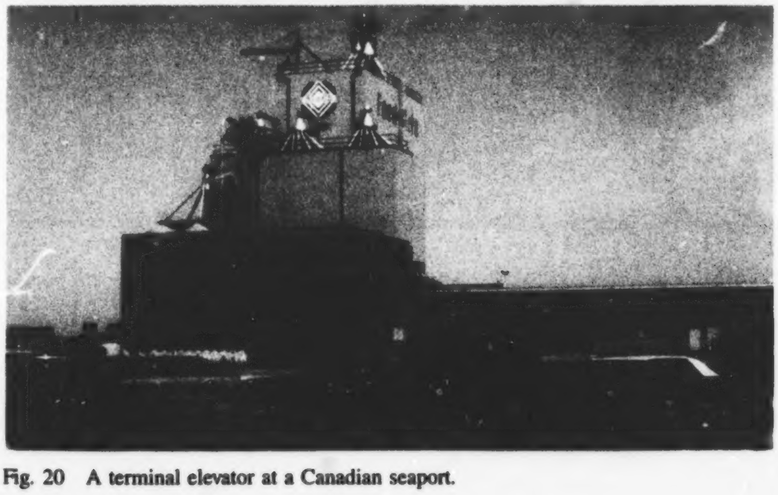

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Fig. 20 A terminal elevator at a Canadian seaport.

Fig. 21 A flour mill in central Canada.

Fig. 22 A feed mill in central Canada.

Only a few insecticides and fumigants are officially registered for use to control stored-product insects in Canada. These insecticides are selected on the basis of their efficacy and negligible risk to the health of humans and animals. The Pesticides Division of the Food Production and Inspection Branch of Agriculture Canada is also responsible for the registration of pest control products, taking into consideration all aspects of the toxicology of compounds that are evaluated. Only those that meet the requirements for usage are registered, after consultation with other regulatory agencies and with the Research Branch.

CHAPTER 9 ANALYSIS AND INTERPRETATION OF PHYTOSANITARY INSPECTION REPORTS

The mill and elevator inspection reports used in this analysis were initially prepared as a prerequisite to issuing phytosanitary certificates according to Agriculture Canada inspection guidelines included in the "Ship, Mill, and Elevator Manual 2" (unpublished, for departmental use only). The manual provides a system of uniform inspection and reporting procedures in the districts and offices of the Food Production and Inspection Branch of Agriculture Canada. The reports are prepared to ensure that the general public, particularly foreign buyers, are provided with high-quality cereals and cereal products.

Seasonal infestation in Canada

For the period 1969–1981, inspection reports from various parts of Canada (Fig. 23) were divided into three major categories concerned with grain storage: grain elevators, flour mills, and feed mills that provide storage, handling, and processing facilities (Table 3). It should be noted that some storage premises have been repeatedly and irregularly inspected during one year as well as over several years. Consequently, some cities, such as Toronto and Montreal, have yielded more reports than others. Results of the following analysis should be interpreted with this limitation in mind. These reports were again divided into 12 groups, based on the number of seasonal inspections of the three major types of storage premises. Although seasonal groups were often adequately sampled, most samples were taken in the fall. Arthropod infestations of cereals and cereal products were common in 52–69% of all reports during 1969–1981. The highest level of infestation (69%) occurred in flour mills (Table 4). Seasonal infestation levels in the premises ranged from 31% in the winter in grain elevators to 74% in the fall in flour mills. Most infestations (73–74%) in flour mills occurred during summer and fall, with the fewest occurring in spring. In elevators, most infestations occurred in fall and summer and the fewest in winter. In feed mills, however, infestation levels fluctuated between 50 and 59% throughout the year.

Association of major insects and mites with various foods and habitats

Various insects, mites, and other arthropods were reported during 1969–1981 by inspectors of the Food Production and Inspection Branch of Agriculture Canada from flour mills, grain elevators, feed mills, and other storage premises that contained cereals, oilseeds, and their products. The Latin names of the species, genus, family, and order of arthropods are verified for their scientific accuracy and are then assigned to their respective higher categories (order and family) as they appeared in inspection reports (Appendix I). It should be mentioned that arthropod identifications by field inspectors with various levels of entomological training and experience might have allowed the inclusion of a few incorrectly identified species in the present list. Unfortunately, in the absence of preserved insect specimens,

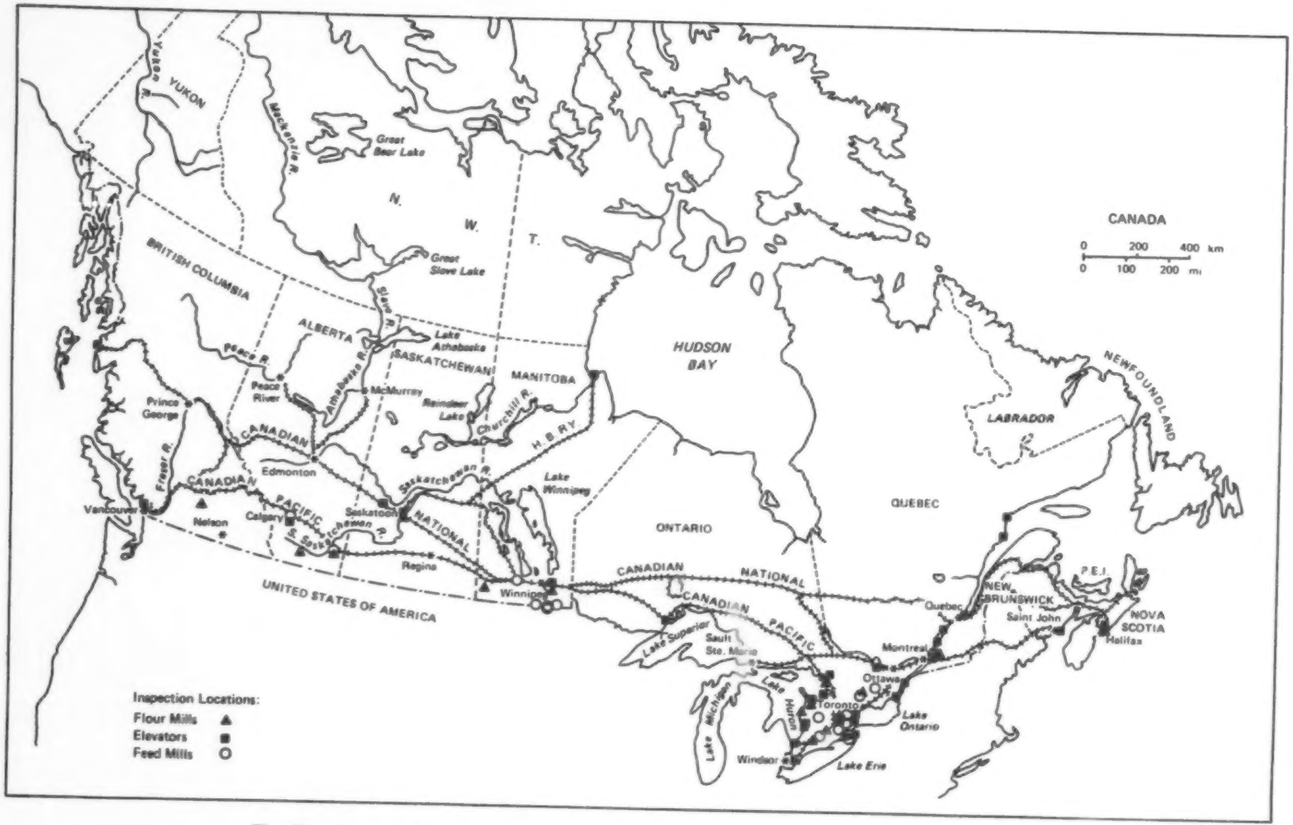

Fig. 23 A map of Canada showing the locations and types of storage facilities that were inspected and that received phytosanitary certificates between 1969 and 1981.

Table 3. **Arthropod occurrence in Canada (1969–1981)**

Region	Type of premises*	All year	Summer	Autumn	Winter	Spring
CANADA						
no. of inspection reports	flm	1019	235	281	265	238
	elev	1095	286	313	234	262
	fdm	413	92	121	101	99
reports of infestation (%)	flm	69	73	74	66	62
	elev	52	66	67	31	37
	fdm	55	57	59	54	50
no. of kinds of arthropods	flm	62	46	43	34	31
	elev	70	55	54	28	39
	fdm	53	37	38	26	29
total arthropod occurrence	flm	1186	315	335	269	267
	elev	1312	456	587	109	159
	fdm	599	189	176	102	132
PROVINCES						
British Columbia						
no. of inspection reports	flm	25	7	8	6	4
	elev	21	8	5	2	6
	fdm	0	0	0	0	0
reports of infestation (%)	flm	76	86	88	67	50
	elev	95	100	100	100	83
	fdm	—	—	—	—	—
no. of kinds of arthropods	flm	8	4	5	3	1
	elev	32	25	14	11	12
	fdm	—	—	—	—	—

Table 3. Arthropod occurrence in Canada (1969–1981) *(continued)*

Region	Type of premises*	All year	Summer	Autumn	Winter	Spring
total arthropod occurrence	flm	23	7	8	6	2
	elev	103	48	24	13	18
	fdm	—	—	—	—	—
Prairie Provinces						
no. of inspection reports	flm	203	35	61	54	53
	elev	24	8	9	3	4
	fdm	92	13	36	22	21
reports of infestation (%)	flm	70	77	74	69	62
	elev	17	13	22	0	25
	fdm	52	69	53	46	48
no. of kinds of arthropods	flm	19	7	10	8	13
	elev	4	1	2	0	1
	fdm	16	9	12	5	9
total arthropod occurrence	flm	182	34	54	42	52
	elev	4	1	2	0	1
	fdm	91	18	38	16	19
Ontario (Thunder Bay)						
no. of inspection reports	flm	0	0	0	0	0
	elev	151	34	36	43	38
	fdm	0	0	0	0	0
reports of infestation (%)	flm	—	—	—	—	—
	elev	39	47	72	19	24
	fdm	—	—	—	—	—

no. of kinds of arthropods	flm	—	—	—	—	—
	elev	19	13	15	5	8
	fdm	—	—	—	—	—
total arthropod occurrence	flm	—	—	—	—	—
	elev	98	29	50	8	11
	fdm	—	—	—	—	—
Ontario						
no. of inspection reports	flm	372	85	99	102	86
	elev	307	75	85	79	68
	fdm	239	58	63	60	58
reports of infestation (%)	flm	70	78	76	65	64
	elev	55	67	79	30	43
	fdm	69	67	78	70	60
no. of kinds of arthropods	flm	48	37	33	29	22
	elev	40	27	29	15	24
	fdm	49	36	33	23	27
total arthropod occurrence	flm	580	162	149	136	133
	elev	393	123	180	36	54
	fdm	494	167	134	84	109
Quebec						
no. of inspection reports	flm	362	94	99	87	82
	elev	502	136	152	85	129
	fdm	82	21	22	19	20
reports of infestation (%)	flm	72	76	74	71	66
	elev	45	60	57	25	30
	fdm	16	19	14	11	20

Table 3. Arthropod occurrence in Canada (1969–1981) *(concluded)*

Region	Type of premises*	All year	Summer	Autumn	Winter	Spring
no. of kinds of arthropods	flm	28	22	22	11	12
	elev	47	32	37	13	20
	fdm	4	2	2	2	1
total arthropod occurrence	flm	374	109	113	76	76
	elev	644	215	323	35	71
	fdm	14	4	4	2	4
Maritime Provinces						
no. of inspection reports	flm	57	14	14	16	13
	elev	90	25	26	22	17
	fdm	—	—	—	—	—
reports of infestation (%)	flm	35	14	57	44	23
	elev	79	96	96	59	53
	fdm	—	—	—	—	—
no. of kinds of arthropods	flm	6	2	4	4	2
	elev	24	19	12	8	5
	fdm	—	—	—	—	—
total arthropod occurrence	flm	27	3	11	9	4
	elev	167	69	58	25	15
	fdm	—	—	—	—	—

* flm, flour mills; elev, elevators; fdm, feed mills (including warehouses).

Note: In terms of arthropod abundance in Canada, the seasons rank in descending order as follows: flm: autumn, summer, winter, spring; elev: autumn, summer, spring, winter; fdm: summer, autumn, spring, winter.

Table 4. Frequency of occurrence and rank of 10 most common insects in flour mills in Canada (1969–1981)

Rank	Insect $n = 94^*$	Occurrence in reports (%)	Incidence in food material			Incidence in each location		
			Wheat $n = 33^*$ (%)	Flour $n = 94^*$ (%)	Dust, debris $n = 104^*$ (%)	Equipment, boots $n = 193^*$ (%)	Walls, floor $n = 585^*$ (%)	Several locations $n = 125^*$ (%)
1	*Tribolium castaneum*	25	6	61	16	19	20	50
2	*Tribolium confusum*	20	3	15	29	22	21	19
3	*Tribolium* spp.	7	0	5	14	4	7	10
4	*Attagenus* spp.	5	3	1	4	3	8	4
5	*Sitophilus granarius*	4	21	2	2	7	4	2
6	*Gibbium psylloides*	3	0	0	1	2	6	2
7	*Tenebrio molitor*	3	6	1	4	4	3	2
8	*Cryptolestes pusillus*	3	6	0	3	9	1	3
9	*Cryptolestes ferrugineus*	3	24	1	3	6	1	2
10	*Tenebroides mauritanicus*	3	9	1	2	3	3	0

* n = number of reports. Total number is 1019; 69% of reports indicated infestation.

such errors cannot be corrected. The analysis of the results presented in this report should therefore be interpreted with this limitation in mind.

Ninety-five kinds of arthropods were associated with the three types of premises (Appendix I). Many of these arthropods, identified to their current taxonomic levels, are pests of economic importance. Several insects—whether identified to specific, generic, family, order, or higher levels—were, however, incidental occurrences considered to be of negligible economic importance. The maps show the distribution of various insect pests in flour mills, grain elevators, and feed mills in Canada. Grain elevators had the greatest variety, with 70 kinds of arthropods appearing in the reports (Table 3). Less diversity of species occurred in winter and spring as compared with summer and autumn.

Common insects in flour mills

Of the 1019 inspection reports of Canadian flour mills, 69% mentioned insect incidence. The 10 most common insects in flour mills are listed in Table 4. Of these, *Tribolium castaneum* and *T. confusum* were the two most common species, occurring in 25% and 20%, respectively, of all reports. After *Tribolium* spp., *Attagenus* spp. and *Sitophilus granarius* were the most common. Two large stored-product insects, *Tenebrio molitor* and *Tenebroides mauritanicus*, were also among the top 10 insects. *Cryptolestes ferrugineus*, the most important stored grain pest in Western Canada, was ninth in rank. In flour mills, *Tribolium castaneum* was found most often in flour, whereas *T. confusum* was found mainly in dust and debris. Both species were equally common in milling equipment, elevator boots, walls, and floor habitats. *Sitophilus granarius* and *C. ferrugineus* were most common on whole wheat in elevator boots. Wheat was also the most preferred food of *Tenebroides mauritanicus*, *Tenebrio molitor*, and *C. pusillus*. *Attagenus* spp. and *Gibbium psylloides* were more commonly found on walls and floors than in elevator boots.

Common insects in grain elevators

Of 1095 elevator inspection reports, 52% mentioned insects or mites. The 10 most common insects in grain elevators are listed in Table 5. In frequency of occurrence, *Tenebrio molitor*, *Nemapogon granella*, and *Attagenus* spp. were the three top insects, appearing in 17%, 14%, and 10% of the total reports, respectively. The next three most common arthropods, which appeared in 5–7% of the reports, were *Cryptolestes ferrugineus*, mites, and *Sitophilus granarius*. *S. oryzae* was among the top 10 most common insects, even though this species does not occur in grain elevators and on farms in the Prairie Provinces, where much Canadian grain is produced and stored.

In grain elevators, *T. molitor* was usually found in grain dust and debris and in wheat, with a frequency of 20% and 14%, respectively. *T. molitor* occurred more or less uniformly in all three habitats: elevator boots, floors, and empty bins.

Nemapogon granella was more commonly associated with stored wheat and other commodities, with the following frequency in the inspection reports: wheat 22%, dust and debris 11%, barley 10%, soybean 9%, and corn 6%. *N. granella* had similar occurrences in all locations (Table 5).

Table 5. Frequency of occurrence and rank of 10 most common insects in grain elevators in Canada (1969–1981)

			Incidence in food material					Incidence in each location			
Rank	Insect or mite $n = 94$*	Occurrence in reports (%)	Wheat $n = 151$* (%)	Barley $n = 39$* (%)	Corn $n = 51$* (%)	Soybean $n = 11$* (%)	Dust, debris $n = 169$* (%)	Equipment, boots $n = 156$* (%)	Walls, floor $n = 273$* (%)	Empty bins $n = 72$* (%)	Several locations $n = 103$* (%)
1	*Tenebrio molitor*	17	14	0	0	0	20	19	22	18	26
2	*Nemapogon granella*	14	22	10	6	9	11	15	12	11	13
3	*Attagenus* spp.	10	3	15	0	0	20	5	14	8	15
4	*Cryptolestes ferrugineus*	7	8	18	12	9	3	5	3	6	5
5	Mites	5	13	8	2	0	1	3	3	6	6
6	*Sitophilus granarius*	5	4	3	16	27	4	3	4	8	4
7	*Cryptolestes pusillus*	3	9	5	8	9	7	1	0	4	2
8	*Sitophilus oryzae*	3	3	0	18	18	2	1	2	6	1
9	*Pyralis farinalis*	3	1	3	2	0	3	5	4	3	2
10	*Tenebroides mauritanicus*	3	1	3	12	18	1	1	3	8	0

* n = number of reports. Total number is 1095; 52% of reports indicated infestation.

Attagenus spp. was most commonly found in dust and debris, although it occurred frequently on barley and to a lesser extent on wheat. It did not occur on corn and soybean. These insects occurred in several locations, especially on walls and floors, but showed no particular preference for a single habitat.

C. ferrugineus occurred in stored commodities, with the following frequencies: barley 18%, corn 12%, soybean 9%, wheat 8%, and dust and debris 3%. Its relatively low frequency of occurrence on wheat is noteworthy, because *C. ferrugineus* is a primary pest of wheat. It was relatively common in all habitats. *Cryptolestes pusillus* occurred to a similar extent on all stored crops and on dust and debris; however, it was less frequently associated with barley.

S. granarius was most commonly found on soybean and corn, and less so on wheat and barley. It occurred more frequently in empty bins than in other habitats. *S. oryzae* most commonly occurred on corn and soybean, but not on barley. It also occurred more frequently in empty bins than in any other habitat.

Tenebroides mauritanicus was most commonly found on soybean and corn. It was more noticeable in empty bins than in other habitats.

Pyralis farinalis occurred infrequently in all habitats and crops investigated, with the exception of soybean, on which it did not occur.

The frequency of occurrence of mites on stored products was as follows: wheat 13%, barley 8%, corn 2%, and soybean 0%. Empty bins were the most common habitat for mites (Table 5).

Common insects and mites in feed mills and warehouses

Of 413 inspection reports, 55% mentioned cases of insect infestation. The 10 most common insects in feed mills (including warehouses) are listed in order of their frequency of occurrence in Table 6. As in the flour mills, *Tribolium castaneum* and *T. confusum* were the two most common insects, appearing in 14% and 13%, respectively, of the total number of reports. Thereafter, *Attagenus* spp. appeared in 12% of the reports and *Nemapogon granella*, *Cryptolestes ferrugineus*, and *Tenebrio molitor* each appeared in 6% of the reports. Two other insects that were not among the top 10 most common kinds of insects in flour mills and grain elevators were *Oryzaephilus surinamensis* and *Plodia interpunctella*. The former species occurred in 5% of the reports and the latter in 4%. As in all other granary categories, *Tenebroides mauritanicus* was the tenth most common insect in feed mills and warehouses.

In feed mills and warehouses, *Tribolium castaneum* was most frequently found in dust and debris. It was found in several habitats, particularly along the walls and floors. *T. confusum* occurred with an 8% frequency on soybean and on dust and debris. It was found in various habitats with the following frequency: several locations 27%, equipment boots 22%, empty bins 13%, and walls and floors 10%.

Attagenus spp. were most commonly associated with wheat, with a 27% frequency. These insects occurred in different habitats with the following frequency: walls and floors 17%, miscellaneous locations 10%, empty bins 6%, and equipment boots 5%.

Table 6. Frequency of occurrence and rank of 10 most common insects in feed mills in Canada (1969–1981)

			Incidence in food material			Incidence in each location			
Rank	Insect or mite $n = 94$*	Occurrence in reports (%)	Wheat $n = 11$* (%)	Soybean $n = 25$* (%)	Dust, debris $n = 83$* (%)	Equipment, boots $n = 81$* (%)	Wall, floor $n = 260$* (%)	Empty bins $n = 16$* (%)	Several locations $n = 52$* (%)
1	*Tribolium castaneum*	14	0	8	15	10	17	0	21
2	*Tribolium confusum*	13	0	8	8	22	10	13	27
3	*Attagenus* spp.	12	27	0	11	5	17	6	10
4	*Nemapogon granella*	6	9	20	6	6	3	19	8
5	*Cryptolestes ferrugineus*	6	9	24	6	5	2	6	2
6	*Tenebrio molitor*	6	0	4	6	6	5	13	4
7	*Oryzaephilus surinamensis*	5	0	0	2	12	4	0	4
8	*Plodia interpunctella*	4	18	0	6	4	3	0	0
9	*Tribolium* spp.	4	0	0	4	3	4	0	10
10	*Tenebroides mauritanicus*	3	9	0	6	4	2	6	0

* n = number of reports. Total number is 413; 55% of reports indicated infestation.

Nemapogon granella was most commonly associated with soybean and less frequently with wheat and dust and debris. Its frequency of occurrence in various habitats was as follows: empty bins 19%, several locations 8%, equipment boots 6%, and walls and floors 3%. In elevators, however, this moth species was most common on wheat, while occurring more or less uniformly in all habitats (Table 5).

Cryptolestes ferrugineus was found in several foods, with the following frequency: soybean 24%, wheat 9%, and dust and debris 6%. This species was more common in empty bins and equipment boots than along walls and floors.

Tenebrio molitor most commonly occurred in dust and debris and in empty bins (Table 6). Dust and debris were also the most favorable food substrate for this species in grain elevators (Table 5).

Oryzaephilus surinamensis occurred in dust and debris but in none of the foods. Its frequency in various habitats was as follows: equipment boots 12% and walls and floors 4%.

Plodia interpunctella was most commonly found on wheat, although it occurred also in dust and debris. Equipment boots, walls, and floors were its favored habitat.

Tenebroides mauritanicus occurred on wheat and dust debris in all types of habitats.

Seasonal infestation in British Columbia

Food-storage premises inspected in British Columbia did not include the feed-mill category. Less than 50 inspection reports covered the other two categories (Table 3). Thus, any generalizations on infestation levels for this province should be made with caution. The infestation levels of elevators and flour mills in the province were 95% and 76%, respectively (Table 3).

Elevators were infested in all seasons. Infestation levels in flour mills ranged from 86–88% in autumn and summer to 50% in spring. The elevators, which had 32 kinds of arthropods, showed greater diversity of insect populations than did flour mills, which had only eight kinds of arthropods. In elevators, more than twice as many kinds of arthropods were found in summer than in any other season. In flour mills no more than five kinds of arthropods were found in any season. In terms of total arthropod occurrence, elevators were most heavily infested in summer and progressively less so during autumn, spring, and winter. The infestation levels in flour mills were relatively low in all seasons compared with those of the elevators.

Seasonal infestation in the Prairie Provinces

Most inspection reports in the Prairie Provinces were from flour mills, which had 203 reports as compared with 24 from terminal elevators and 92 from feed mills (Table 3). All premises and all seasons, however, were represented in the sampling. The seasonal infestation levels peaked in summer in flour and feed mills; more than 46% of the reports recorded infestation in all four seasons (Table 3). The levels in the grain elevators, however, were relatively low, ranging from a high of 25% in spring to a low of zero in winter. A greater diversity of arthropods occurred in flour and feed mills than in grain elevators. The greatest variety of arthropods and the season in which they were found were as follows: flour mills, 13 kinds in the spring; elevators, two kinds in autumn; and in feed mills, 12 kinds in the autumn (Table 3).

In terms of total arthropod occurrence, flour mills were most frequently infested in autumn and spring, and progressively less so in winter and summer. Feed mills were most infested in autumn, with progressively less infestation in spring, summer, and winter. In the prairie grain elevators, infestation in all seasons was negligible or did not occur at all.

Seasonal infestation in Thunder Bay, Ontario

Thunder Bay, Ont., has been treated as a separate region in this report because of its large concentration of terminal elevators and its more severe climate compared with that of southern Ontario, where many other storage premises are located. Grain elevators were the only type of building inspected in Thunder Bay; the number of inspection reports per season ranged from 34 to 43 (Table 3). The highest level of infestation, 72%, was recorded in autumn and the lowest, 19%, in winter. Autumn was also the most important season in terms of arthropod diversity and total occurrence.

Seasonal infestation in eastern Ontario

Inspection reports from eastern and southern Ontario were well represented in the three categories of premises and four seasonal groups. The largest number of reports was from flour mills, followed by grain elevators and feed mills. None of the seasons had less than 58 reports (Table 3). Arthropods were recorded in 55–70% of the reports for all year. Except for grain elevators during winter and spring, all premises had a frequency of infestation that was 60% or higher in every season of the year. In flour mills, infestation was 76–78% during summer and autumn, and 64–65% during winter and spring. In grain elevators, the infestation level peaked at 79% in autumn and then declined to 30% in winter. In feed mills, corresponding peaks also occurred in autumn (78%), the winter level remained relatively high at 70%, and the lowest level was only 60% in spring.

Arthropod infestation was more diverse in the storage premises of Ontario than in any other region of the country; from 40 to 49 different kinds of arthropods occurred (Table 3). The greatest variety of arthropods, 36–37 kinds, was found in summer in flour mills and feed mills, where no less than 22 kinds of arthropods occurred in every season. In grain elevators, however, a maximum of 29 kinds of arthropods occurred in autumn, as compared with a minimum of 15 kinds in winter. Ontario flour mills had a greater frequency of occurrence of infestation than did feed mills and elevators. Many arthropods occurred in all seasons, except in winter and spring in grain elevators and adjoining storage premises. Thus, flour mills and feed mills in southern Ontario, where most premises are located, are vulnerable to invasion by arthropod pests on a year-round basis. Grain elevators are relatively less susceptible to invasion during winter and spring.

Seasonal infestation in Quebec

Quebec inspection reports were better represented from grain elevators and flour mills than from feed mills (Table 3). The number of reports within each category of premises, however, was well distributed among the four seasons. Arthropod infestation recorded in reports were as follows: flour mills 72%, grain elevators 45%, and feed mills 16%. Flour mill infestation remained at an unusually high 66–76% in all seasons. Winter infestation levels did not go below 71%. In grain elevators, however, infestation levels were considerably higher—from 57 to 60% in summer and autumn and from 25 to 30% in winter and spring. In feed mills more infestations occurred in spring and summer than in autumn and winter.

Diversity of arthropods was conspicuous in the storage premises of Quebec. Grain elevators had as many as 47 kinds of arthropods, flour mills 28 kinds, and feed mills only four kinds (Table 3). In flour mills, about twice as many kinds of arthropods occurred in summer and autumn (22) as in winter and spring (11–12). In grain elevators, 37 kinds of arthropods were found in autumn, 32 in summer, 20 in spring, and only 13 in winter. In feed mills, only two kinds of arthropods were found in all seasons except in spring, when only one kind was recorded.

Of 644 occurrences throughout the year, the highest, 323, occurred in autumn, 215 in summer, 71 in spring, and only 35 in winter. Feed mills had only four occurrences in all seasons except winter, when only two occurrences were reported.

Seasonal infestation in the Maritime Provinces

More infestation reports were made on grain elevators than on flour mills; no reports were available for feed mills (Table 3). These reports were reasonably well distributed among the four seasons. More than twice as many infestations occurred in grain elevators as did in flour mills throughout the year. Levels of seasonal flour-mill infestation in the Maritime Provinces varied throughout the year: 57% in autumn, 44% in winter, 23% in spring, and only 14% in summer. Grain elevators were always infested at 96% in summer and autumn and only at 53–59% in winter and spring. Only six kinds of arthropods were found in flour mills as compared with 24 kinds in grain elevators. Arthropod occurrence for flour mills was relatively light as compared with grain elevators. In flour mills, arthropods were more abundant in autumn and winter than in spring and summer. In the grain elevators, however, the peak season for arthropod abundance was summer. Arthropods were progressively less abundant through autumn, winter, and spring.

Major flour mill pests in Canadian cities and their national status

Armstrong, B.C.

Six kinds of insects and mites were found in a flour mill in Armstrong. Of these, the confused flour beetle, *Tribolium confusum*, was the most common, occurring in 57% of the reports (Table 7). The incidence level of *T. confusum* in

Table 7. Frequency of occurrence of stored-product arthropods in flour mills in five cities in Western Canada as a percentage of total occurrence (1969–1981)

Arthropod	Armstrong, B.C. $n=23$* (%)	Percentage of Canadian reports	Lethbridge, Alta. $n=34$* (%)	Percentage of Canadian reports	Medicine Hat, Alta. $n=25$* (%)	Percentage of Canadian reports	Saskatoon, Sask. $n=42$* (%)	Percentage of Canadian reports	Winnipeg, Man. $n=75$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (n)*
Tribolium castaneum	4	†	6	1	8	1	0	0	1	†	295
Tribolium confusum	57	6	38	6	40	4	71	13	81	26	233
Tribolium spp.	17	5	29	12	32	10	2	1	0	0	82
Attagenus spp.	4	2	12	6	4	2	0	0	5	6	65
Sitophilus granarius	0	0	0	0	0	0	0	0	1	2	51
Cryptolestes ferrugineus	4	3	0	0	0	0	0	0	0	0	34
Cryptolestes pusillus	0	0	0	0	0	0	0	0	1	3	34
Tenebroides mauritanicus	0	0	0	0	0	0	0	0	3	6	32
Ptinus spp.	0	0	0	0	0	0	2	3	0	0	31
Ephestia kuehniella	0	0	0	0	4	4	0	0	1	4	26
Trogoderma inclusum	0	0	9	15	8	10	14	30	0	0	20
Sitophilus oryzae	0	0	0	0	0	0	0	0	3	11	19
Dermestidae	0	0	0	0	0	0	2	6	1	6	16
Mites	4	13	0	0	0	0	0	0	0	0	8
Ptinus villiger	0	0	0	0	0	0	5	40	0	0	5
Anthrenus verbasci	0	0	0	0	0	0	0	0	1	25	4
Cathartus quadricollis	0	0	0	0	0	0	2	50	0	0	2
Lepisma saccharina	0	0	6	100	0	0	0	0	0	0	2

* n = number of reports. Total number of reports in Canada, 1019.

† Less than 1%.

Armstrong, B.C., represented 6% of the national level for this species. Mites constituted 4% of the pest incidence reports at Armstrong, but 13% of the national level of incidence for this arthropod pest.

Lethbridge, Alta.

Six kinds of insects were generally found in flour mills in Lethbridge. Of these, *Tribolium confusum* was the most common species, occurring in 38% of the reports (Table 7). This was 6% of the national level of incidence for this species. The red flour beetle, *T. castaneum*, also occurred here, but its incidence level was only 1% of the national level for this species. Next to *Tribolium* spp., *Attagenus* spp. were the most common kind of insect, with 6% of the national incidence level for this insect group. *Trogoderma inclusum* occurred in 9% of the reports from Lethbridge. Its incidence level, however, made up 15% of the national level for this species. Silverfish, *Lepisma saccharina*, constituted 6% of incidence reports, but Lethbridge was the only location in Canada where it was formally reported.

Medicine Hat, Alta.

Flour mills in Medicine Hat were infested with six kinds of insects (Table 7). Although several species of *Tribolium* were found, *T. confusum* was most common, occurring in 40% of the reports. *Trogoderma inclusum* was also common in this city; its incidence level made up 8% of all city infestations and 10% of the national level. *Ephestia kuehniella* was also found, but it was relatively scarce.

Saskatoon, Sask.

Seven kinds of insects usually invaded flour mills in Saskatoon (Table 7). Of these, *Tribolium confusum* was the most common, occurring in 71% of the reports. It made up 13% of the national level of incidence for this insect species. *Trogoderma inclusum* was the second most important insect pest of flour mills. Although only 14% of the city reports included this species, this figure represents 30% of the national incidence level for this species. The hairy spider beetle, *Ptinus villiger*, was the third most common flour mill insect pest in Saskatoon. Its incidence made up 40% of the national level for this species. Some of the less common flour mill pests belonged to the family Dermestidae and the spider beetle genus *Ptinus*.

Winnipeg, Man.

Winnipeg flour mills were usually infested with 10 kinds of insects. Of these, *Tribolium confusum* was the most common species, occurring in 81% of the reports (Table 7). It made up 26% of the national incidence level for this species. Nine kinds of insects were relatively less common as compared with *T. confusum*, because none of them made up more than 5% of the total frequency of occurrence of insects in this city. These were *T. castaneum*, *Attagenus* spp. (considered as one kind of insect), *Sitophilus granarius*, *S. oryzae*, *Cryptolestes pusillus*, *Tenebroides mauritanicus*, *Ephestia kuehniella*, *Anthrenus verbasci*, and other dermestid beetles.

Chatham, Ont.

Flour mills in Chatham were usually infested with 18 different kinds of insects (Table 8). The most common was, as elsewhere, *Tribolium confusum*, which occurred in 36% of the infestation reports from this city; its incidence level made up only 14% of the national level. The other common insects in Chatham flour mills, in order of their frequency of occurrence, were *Ptinus* spp., *Attagenus* spp., *Trogoderma inclusum*, and *Tenebroides mauritanicus*. Some of the less common insects included *Sitophilus granarius*, *Tenebrio molitor*, *Anthrenus scrophulariae*, and *Cynaeus angustus*.

Hanover, Ont.

Flour mills in Hanover were usually infested by nine kinds of insects (Table 8). Of these, *Tribolium* spp. were most common, occurring in 44% of the reports. *Tenebroides mauritanicus* was the second most common insect. Its 19% incidence level here also represented 19% of the national level for this species. The other kinds of insects that were relatively less common, in order of their frequency of occurrence were: *Tenebrio molitor*, *Sitophilus granarius*, Dermestidae, *Attagenus* spp., *Ptinus* spp., *Oryzaephilus surinamensis*, and *Ptinus villiger*. The incidence level of *P. villiger* in Hanover made up 20% of the national level for this species.

Woodstock, Ont.

Flour mills in Woodstock were usually infested with 10 kinds of insects (Table 8). Of these, *Tribolium confusum* was the most common, occurring in 32% of the reports from this city. Four other arthropods were also relatively common: *Tenebrio molitor*, *Sitophilus granarius*, *Cryptolestes pusillus*, and a sowbug (Isopoda). The less common insects, in order of the frequency of occurrence, were *Tribolium* spp., *Attagenus* spp., *Tribolium castaneum*, *Oryzaephilus surinamensis*, and *Dermestes lardarius*.

Streetsville, Ont.

Flour mills in Streetsville were infested with 21 species of insects (Table 9). The most common species, a spider beetle, *Gibbium psylloides*, occurred in 23% of the reports from this city. Of the 40 reports of incidence of this species in Canada, 98% were reported from Streetsville. *Tribolium confusum* was the second most common insect species, occurring in 19% of the reports. Other kinds of relatively common insects that occurred in at least 5% of the reports in order of their

Table 8. Frequency of occurrence of stored-product arthropods in flour mills in three cities in western Ontario as a percentage of total occurrence (1969–1981)

Arthropod	Chatham $n = 93$* (%)	Percentage of Canadian reports	Hanover $n = 32$* (%)	Percentage of Canadian reports	Woodstock $n = 38$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (n)*
Tribolium castaneum	1	†	0	0	3	†	295
Tribolium confusum	36	14	0	0	32	5	233
Tribolium spp.	1	1	44	17	5	2	82
Attagenus spp.	14	20	3	2	5	3	65
Sitophilus granarius	2	4	6	4	13	10	51
Gibbium psylloides	1	3	0	0	0	0	40
Tenebrio molitor	2	5	9	8	16	15	40
Cryptolestes ferrugineus	1	3	0	0	0	0	34
Cryptolestes pusillus	1	3	0	0	8	9	34
Tenebroides mauritanicus	5	16	19	19	0	0	32
Ptinus spp.	19	58	3	3	0	0	31
Trogoderma inclusum	8	35	0	0	0	0	20
Oryzaephilus surinamensis	1	6	3	5	3	6	18
Dermestidae	0	0	6	13	0	0	16
Mites	1	13	0	0	0	0	8
Trogoderma spp.	1	13	0	0	0	0	8
Dermestes lardarius	0	0	0	0	3	17	6
Ptinus villiger	1	20	3	20	0	0	5
Anthrenus scrophulariae	2	67	0	0	0	0	3
Cynaeus angustus	2	67	0	0	0	0	3
Sowbugs	0	0	0	0	8	100	3

* n = number of reports. Total number of reports in Canada, 1019.

† Less than 1%.

Table 9. Frequency of occurrence of stored-product arthropods in flour mills in three cities in southern and western Ontario as a percentage of total occurrence (1969–1981)

Arthropod	Streetsville $n = 171$* (%)	Percentage of Canadian reports	Port Colborne $n = 164$* (%)	Percentage of Canadian reports	Woodbridge $n = 51$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (*n*)*
Tribolium castaneum	8	5	30	17	2	†	295
Tribolium confusum	19	14	4	3	0	0	233
Tribolium spp.	5	11	0	0	0	0	82
Attagenus spp.	8	22	6	14	2	2	65
Sitophilus granarius	6	20	1	4	8	8	51
Gibbium psylloides	23	98	0	0	0	0	40
Tenebrio molitor	6	25	2	10	0	0	40
Cryptolestes ferrugineus	5	24	2	9	18	27	34
Cryptolestes pusillus	†	3	12	56	0	0	34
Tenebroides mauritanicus	†	3	4	22	2	3	32
Ptinus spp.	6	32	†	3	0	0	31
Ephestia kuehniella	2	15	0	0	31	62	26
Sitophilus oryzae	0	0	0	0	2	5	19
Oryzaephilus surinamensis	1	11	0	0	16	44	18
Dermestidae	†	6	6	63	2	6	16
Typhaea stercorea	3	46	0	0	4	18	11
Nemapogon granella	1	20	3	50	2	10	10
Mites	0	0	4	75	0	0	8
Ahasverus advena	0	0	0	0	6	43	7
Cryptolestes turcicus	0	0	4	100	0	0	7
Pyralis farinalis	1	29	†	14	2	14	7

Table 9. Frequency of occurrence of stored-product arthropods in flour mills in three cities in southern and western Ontario as a percentage of total occurrence (1969–1981) *(concluded)*

Arthropod	Streetsville $n = 171$* (%)	Percentage of Canadian reports	Port Colborne $n = 164$* (%)	Percentage of Canadian reports	Woodbridge $n = 51$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (*n*)*
Cryptolestes spp.	0	0	1	33	0	0	6
Dermestes lardarius	0	0	3	83	0	0	6
Psocoptera	0	0	4	100	0	0	6
Ptinus villiger	0	0	†	20	0	0	5
Anthrenus verbasci	†	25	1	50	0	0	4
Plodia interpunctella	0	0	2	100	0	0	4
Anthicus floralis	†	33	0	0	0	0	3
Cynaeus angustus	0	0	†	33	4	67	3
Haplotinea ditella	0	0	2	100	0	0	3
Mezium americanum	2	100	0	0	0	0	3
Diptera	†	50	†	50	0	0	2
Ptinus ocellus	0	0	1	100	0	0	2
Ptinus tectus	0	0	1	100	0	0	2
Tenebrio obscurus	0	0	1	100	0	0	2

* *n* = number of reports. Total number of reports in Canada, 1019.

† Less than 1%.

frequency of occurrence, were *Tribolium castaneum*, *Attagenus* spp., *Sitophilus granarius*, *Tenebrio molitor*, *Ptinus* spp., *Tribolium* spp., and *Cryptolestes ferrugineus*. Several kinds of insects occurred only occasionally. The more important stored-product pests among them included *Ephestia kuehniella*, *Typhaea stercorea*, *Mezium americanum*, *Oryzaephilus surinamensis*, *Nemapogon granella*, and *Pyralis farinalis*. Incidence levels of *Tenebrio molitor*, *Ptinus* spp., *Attagenus* spp., *Sitophilus granarius*, *Typhaea stercorea*, and *Cryptolestes ferrugineus* made up 20–46% of their national levels in this one location. The only Canadian flour mill records of *Mezium americanum* originated in Streetsville.

Port Colborne, Ont.

Flour mills in Port Colborne were infested with 26 kinds of insects and mites (Table 9). Of these, *Tribolium castaneum* was the most common, occurring in 30% of the reports; it represented 17% of the national incidence level for this species. *Cryptolestes pusillus* was the second most common species, although it occurred in only 12% of the reports from this city. This incidence level represented 56% of the national level for this species. Only two other kinds of insects—*Attagenus* spp. and Dermestidae—occurred in more than 5% of reports. Some of the other less common stored-product pests, in order of their frequency of occurrence in Port Colborne were *Tribolium confusum*, *Tenebroides mauritanicus*, *Cryptolestes turcicus*, mites, Psocoptera, *Nemapogon granella*, *Dermestes lardarius*, *Tenebrio molitor*, *Cryptolestes ferrugineus*, *Plodia interpunctella*, and *Haplotinea ditella*.

The following seven kinds of insects that occurred in flour mills of Port Colborne were not reported from flour mills elsewhere in Canada: *Cryptolestes turcicus*, Psocoptera, *Plodia interpunctella*, *Haplotinea ditella*, *Ptinus ocellus*, *Ptinus tectus*, and *Tenebrio obscurus*. The Port Colborne flour mills harbor more diverse stored-product insect fauna than do the flour mills in most other Canadian cities.

Woodbridge, Ont.

Flour mills in Woodbridge were infested with 14 kinds of insects (Table 9). Of these, *Ephestia kuehniella* was the most common, occurring in 31% of the reports. The incidence level of this species in Woodbridge represented 62% of the national level for this species. *Cryptolestes ferrugineus* and *Oryzaephilus surinamensis* were the only other common flour mill insects, occurring in 18% and 16% of the reports, respectively. The incidence level of *O. surinamensis* made up 44% of the national level for this species. Only two other insects—*Sitophilus granarius* and *Ahasverus advena*—occurred in more than 5% of the reports from this city. Some of the less common insects, in order of their frequency of occurrence, were *Typhaea stercorea*, *Cynaeus angustus*, *Tribolium castaneum*, *Attagenus* spp., *Tenebroides mauritanicus*, *Sitophilus oryzae*, Dermestidae, *Nemapogon granella*, and *Pyralis farinalis*. The incidence levels of *Cynaeus angustus* and *Ahasverus advena* were 67% and 43% of the national levels for these species, respectively.

Montreal, Que.

Flour mills in Montreal were infested with 22 kinds of insects (Table 10). Of these, *Tribolium castaneum* was the most common, occurring in 59% of the reports from this city. Three-quarters of all flour mill reports of *T. castaneum* originated in Montreal. The second most common species, *Sitophilus granarius*, occurred in 7% of the reports, although nearly half of all Canadian incidence reports of *S. granarius* originated in Montreal. Some of the other less common stored-product pests reported from Montreal flour mills, in order of their frequency of occurrence, were *Attagenus* spp., *Tenebrio molitor, Sitophilus oryzae, Tribolium confusum, Cryptolestes ferrugineus, C. pusillus, Tenebroides mauritanicus, Trogoderma* spp., and *Typhaea stercorea*. Only one insect species, *Ptinus hirtellus*, was reported exclusively from Montreal flour mills. A few of the relatively uncommon stored-product insects that appeared in the reports were *Trogoderma inclusum, Alphitobius diaperinus*, and *Cathartus quadricollis*.

Halifax, N.S.

Flour mills of Halifax were infested with only six kinds of insects (Table 10). *Tribolium* spp. were the most common, occurring in 59% of the reports. The incidence level of *Tribolium* spp. made up 20% of the national level for this insect group. *Tribolium destructor* was the second most common insect. Its incidence level (19%) in this city represents all Canadian records for this species. *Tribolium castaneum* was the third most common flour mill pest, occurring in 11% of the reports. Other less common stored-product pests, in order of their frequency of occurrence, were *Tenebroides mauritanicus, Cryptolestes* spp., and *Alphitobius diaperinus*.

Major arthropod pests of grain elevators and their national status

Vancouver, B.C.

Terminal elevators in the Vancouver area were infested with 22 kinds of insects and mites (Table 11). Of these, the brown house moth, *Hofmannophila pseudospretella*, was the most common species, occurring in 17% of the reports. For this species, the incidence level in Vancouver represented 58% of the national level. The whiteshouldered house moth, *Endrosis sarcitrella*, was the second most common insect, occurring in 11% of the city reports. The incidence level for Vancouver represented 83% of the national level for this species. *Tenebrio molitor* was the most common coleopteran pest, occurring in 9% of the reports. Other arthropods were relatively less common and included various insects and mites. Some of these, in order of their frequency of occurrence, were mites, *Ptinus* spp., Lepidoptera spp., staphylinid beetles, *Cryptolestes ferrugineus, Sitophilus granarius, Tinea pallescentella, Cryptophagus cellaris*, Psocoptera, *Pyralis farinalis, Tribolium castaneum*, and *Tribolium confusum*.

Table 10. Frequency of occurrence of stored-product arthropods in flour mills in two cities in Eastern Canada as a percentage of total occurrence (1969–1981)

Arthropod	Montreal, Que. $n = 374$* (%)	Percentage of Canadian reports	Halifax, N.S. $n = 27$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (n)*
Tribolium castaneum	59	75	11	1	295
Tribolium confusum	2	3	0	0	233
Tribolium spp.	1	6	59	20	82
Attagenus spp.	4	20	0	0	65
Sitophilus granarius	7	49	0	0	51
Tenebrio molitor	4	33	0	0	40
Cryptolestes ferrugineus	2	27	0	0	34
Cryptolestes pusillus	2	27	0	0	34
Tenebroides mauritanicus	2	28	4	3	32
Ephestia kuehniella	1	15	0	0	26
Trogoderma inclusum	†	5	0	0	20
Sitophilus oryzae	4	84	0	0	19
Oryzaephilus surinamensis	1	28	0	0	18
Typhaea stercorea	1	36	0	0	11
Nemapogon granella	†	10	0	0	10
Trogoderma spp.	2	88	0	0	8
Ahasverus advena	1	57	0	0	7
Pyralis farinalis	†	43	0	0	7
Cryptolestes spp.	†	50	4	17	6
Alphitobius diaperinus	1	80	4	20	5
Tribolium destructor	0	0	19	100	5
Ptinus hirtellus (= P. clavipes)	†	100	0	0	3
Cathartus quadricollis	†	50	0	0	2

* n = number of reports. Total number of reports in Canada, 1019.

† Less than 1%.

Table 11. Frequency of occurrence of stored-product arthropods in grain elevators in three seaport cities in Canada as a percentage of total occurrence (1969–1981)

Arthropod	Vancouver, B.C. $n = 89$* (%)	Percentage of Canadian reports	St. John, N.B. $n = 79$* (%)	Percentage of Canadian reports	Halifax, N.S. $n = 88$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (n)*
Tenebrio molitor	9	4	23	8	11	5	223
Nemapogon granella	0	0	30	13	42	20	186
Attagenus spp.	2	2	1	†	0	0	126
Cryptolestes ferrugineus	3	3	4	3	3	3	97
Mites	6	8	6	8	24	32	66
Sitophilus granarius	3	5	1	2	0	0	61
Pyralis farinalis	2	5	1	3	1	3	37
Tinea pallescentella	3	10	0	0	0	0	31
Plodia interpunctella	1	4	0	0	0	0	27
Hofmannophila pseudospretella	17	58	0	0	11	39	26
Lepidoptera spp.	6	21	3	8	0	0	24
Cryptolestes spp.	2	10	0	0	0	0	20
Ptinus spp.	6	31	1	6	1	6	16
Cryptophagus cellaris	3	20	0	0	0	0	15
Cryptophagus spp.	2	17	3	17	0	0	12
Endrosis sarcitrella	11	83	0	0	0	0	12
Psocoptera	3	27	1	9	1	9	11
Ptinus villiger	0	0	3	18	1	9	11
Tribolium castaneum	2	20	1	10	0	0	10
Ahasverus advena	0	0	0	0	2	22	9
Alphitobius diaperinus	0	0	1	13	0	0	8

Dermestes lardarius	0	0	5	57	1	14	7
Tribolium confusum	2	29	0	0	0	0	7
Ptinus ocellus	0	0	3	33	0	0	6
Diptera	0	0	1	20	0	0	5
Staphylinidae spp.	5	80	0	0	0	0	5
Tenebrio obscurus	0	0	1	25	0	0	4
Tineola bisselliella	1	25	4	75	0	0	4
Niptus unicolor	2	50	0	0	0	0	4
Tinea pellionella	0	0	3	67	0	0	3
Niptus hololeucus	0	0	3	100	0	0	2
Oryzaephilus mercator	1	50	0	0	0	0	2

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* *n* = number of reports. Total number of reports in Canada, 1095.

† Less than 1%.

Saint John, N.B.

Grain elevators in St. John were infested with 21 kinds of arthropods (Table 11). Two species of insects were far more common than others. *Nemapogon granella* was the most common arthropod species, occurring in 30% of the reports. The incidence level of *N. granella* represented 13% of the national level for this species. *Tenebrio molitor* was the second most common species, occurring in 23% of the reports; its incidence level, however, represented only 8% of the national level for this species. Two other kinds of arthropods occurring in 5–6% of the reports were mites and *Dermestes lardarius*. The incidence level of mites in St. John was 8% of the national level and that of *D. lardarius* was 57% of the national level. The remaining stored-product arthropods that were still less common (1–4% incidence levels) included *Cryptolestes ferrugineus, Tineola bisselliella, Cryptophagus* spp., *Ptinus villiger, P. ocellus, Tinea pellionella, Niptus hololeucus, Attagenus* spp., *Sitophilus granarius, Pyralis farinalis, Tribolium castaneum*, Psocoptera, *Alphitobius diaperinus*, and *Tenebrio obscurus*. The incidence of *N. hololeucus* represented 100% of the national level for this species; the corresponding national level for *Tineola bisselliella* was 75%, for *Tinea pellionella* 67%, for *Ptinus ocellus* 33%, and for *Tenebrio obscurus* 25%.

Halifax, N.S.

Grain elevators in Halifax were infested with 11 kinds of arthropods (Table 11). Of these, four kinds were more common than most others. *Nemapogon granella* was most common, occurring in 42% of the reports. Its incidence level represented 20% of the national level for this species. Mites were the second most common group of arthropod, occurring in 24% of the reports. Their incidence level made up one-third of the national level of this kind of stored-product arthropod pest. Two species that ranked as the third most common arthropods, occurring in 11% of the reports, were *Tenebrio molitor* and *Hofmannophila pseudospretella*. Incidence levels in Halifax as proportions of the national levels, however, varied considerably; the national incidence level was 39% for *H. pseudospretella* as compared with 5% for *T. molitor*. Obviously, *H. pseudospretella* is well adapted to coastal environments such as Halifax and Vancouver. Other arthropods that were less common, occurring in 1–3% of the reports, were *Cryptolestes ferrugineus, Ahasverus advena, Pyralis farinalis, Ptinus* spp., Psocoptera, *Ptinus villiger*, and *Dermestes lardarius*. The incidence level of *A. advena* represented 22% of the national level for this species.

Thunder Bay, Ont.

Terminal elevators in Thunder Bay were infested with 19 kinds of insects and mites (Table 12). Of these, seven kinds of arthropods were relatively common. The European grain moth, *Nemapogon granella*, was the most common species, occurring in 24% of the reports, but its incidence level in Thunder Bay represented only 12% of the national level for this species. *Tenebrio molitor*, mites, and *Cryptolestes ferrugineus* were the second, third, and fourth most common kinds of arthropods occurring in 13%, 12%, and 10% of the reports, respectively. Incidence levels of mites in this city represented 18% of the national level for this arthropod group. Some of the other less common stored-product insects in grain elevators in Thunder Bay, in order of the frequency of occurrence, were as follows: *Cryptophagus* spp., *Attagenus* spp., *Lathridius* spp., *Cryptolestes pusillus*, *Tinea pallescentella*, *Plodia interpunctella*, *Typhaea stercorea*, *Ahasverus advena*, *Haplotinea ditella*, *Oryzaephilus surinamensis*, and *Ptinus ocellus*. The incidence level of *Cryptophagus* spp. represented 58% of the national level for this insect genus.

Goderich, Ont.

The grain elevators in Goderich were infested with 10 kinds of arthropods (Table 12). Of these, three were most common (*Tenebrio molitor*, *Plodia interpunctella*, and mites), occurring in 18% of the reports from this location. The level of *P. interpunctella* represented 11% of the national level for this species. The level of mites represented 5%, whereas *T. molitor* represented only 1% of the national level. *Sitophilus granarius* was the most common stored-product insect, occurring in 12% of the reports. Other less common insects included *Nemapogon granella*, *Attagenus* spp., *Cryptolestes pusillus*, *Sitophilus oryzae*, *Tenebroides mauritanicus*, and Psocoptera. Because the number of reports from this city was only 17, the pattern of insect incidence may not be representative of actual numbers.

Owen Sound, Ont.

Grain elevators in Owen Sound were infested with eight kinds of stored-product insects (Table 12). Of these, three species of insects were more common than others. *Nemapogon granella* was the most common species, appearing in 33% of the reports. Its incidence level, however, represented only 3% of the national level for this species. *Tenebrio molitor* and *Cryptolestes ferrugineus* were the second and third most common species, respectively, occurring in 20% and 13% of the reports.

Other less common insects included *Plodia interpunctella*, *Ephestia kuehniella*, *Ptinus villiger*, *Tribolium castaneum*, and *Ahasverus advena*. Because the analysis of the insect fauna in this city was based on only 15 reports, caution should be used when making generalizations.

Midland, Ont.

Grain elevators in Midland were infested with 17 kinds of insects (Table 12). *Tenebrio molitor* and *Nemapogon granella* were the most common species, each occurring in 20% of the reports from this location. *Cryptolestes ferrugineus* closely followed the other two in frequency of occurrence. The incidence level of *C. ferrugineus* represented 10% of the national level for this species. The other less common insects, in order of their frequency of occurrence, were *Cryptophagus*

Table 12. Frequency of occurrence of stored-product arthropods in grain elevators in four cities in northern and western Ontario as a percentage of total occurrence (1969–1981)

Arthropod	Thunder Bay $n = 98$* (%)	Percentage of Canadian reports	Goderich $n = 17$* (%)	Percentage of Canadian reports	Owen Sound $n = 15$* (%)	Percentage of Canadian reports	Midland $n = 59$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (n)*
Tenebrio molitor	13	6	18	1	20	1	20	5	223
Nemapogon granella	24	12	6	†	33	3	20	7	186
Attagenus spp.	5	4	6	†	0	0	5	2	126
Cryptolestes ferrugineus	10	10	0	0	13	2	17	10	97
Mites	12	18	18	5	0	0	0	0	66
Sitophilus granarius	0	0	12	3	0	0	0	0	61
Cryptolestes pusillus	1	2	6	2	0	0	2	2	43
Pyralis farinalis	0	0	0	0	0	0	5	8	37
Sitophilus oryzae	0	0	6	3	0	0	0	0	37
Tenebroides mauritanicus	0	0	6	3	0	0	5	8	36
Tinea pallescentella	1	3	0	0	0	0	3	7	31
Plodia interpunctella	1	4	18	11	7	4	0	0	27
Lepidoptera	9	38	0	0	0	0	2	4	24
Ephestia kuehniella	0	0	0	0	7	5	2	5	21
Ptinus spp.	1	6	0	0	0	0	2	6	16
Cryptophagus cellaris	7	47	0	0	0	0	7	27	15
Typhaea stercorea	1	7	0	0	0	0	2	7	15
Cryptophagus spp.	7	58	0	0	0	0	0	0	12
Psocoptera	0	0	6	9	0	0	0	0	11
Ptinus villiger	0	0	0	0	7	9	0	0	11
Tribolium castaneum	0	0	0	0	7	10	2	10	10
Ahasverus advena	1	11	0	0	7	11	0	0	9

Haplotinea ditella	1	11	0	0	0	0	2	11	9
Lathridius spp.	2	33	0	0	0	0	3	33	6
Oryzaephilus surinamensis	1	17	0	0	0	0	0	0	6
Ptinus ocellus	1	17	0	0	0	0	0	0	6
Diptera	1	20	0	0	0	0	2	20	5

* n = number of reports. Total number of reports in Canada, 1095.

† Less than 1%.

cellaris, *Attagenus* spp., *Tenebroides mauritanicus*, *Pyralis farinalis*, *Tinea pallescentella*, and *Lathridius* spp. The following insects were relatively scarce, occurring only in 2% of the reports: *Cryptolestes pusillus*, *Ephestia kuehniella*, and *Ptinus* spp.

Toronto, Ont.

Grain elevators in Toronto were infested with 25 kinds of insects and mites (Table 13). The three most common kinds, *Tenebrio molitor*, *Cryptolestes ferrugineus*, and *Attagenus* spp., occurred in 15%, 14%, and 10% of the reports, respectively. The incidence level of *C. ferrugineus* represented 12% of the national level for this species. Other less common kinds of arthropods (4–6% incidence), in order of their frequency of occurrence, were *Ptinus villiger*, *Nemapogon granella*, *Sitophilus granarius*, *Pselaphochernes parvus* (a pseudoscorpion), *Pyralis farinalis*, *Plodia interpunctella*, and *Oryzaephilus surinamensis*. The following arthropods appeared in only 1–2% of the reports and are therefore relatively scarce in Toronto elevators: mites, *Tenebroides mauritanicus*, *Ahasversus advena*, *Tribolium confusum*, *Tinea pallescentella*, *Typhaea stercorea*, *Ptinus ocellus*, and *P. fur*. Three kinds of pseudoscorpions occurred almost exclusively in Toronto elevators.

Port Colborne, Ont.

Grain elevators in Port Colborne were infested with 12 kinds of insects and mites (Table 13), but because there was only a total of 21 reports, the number of arthropod types in this location could be higher. *Tenebrio molitor* was the most common arthropod, occurring in 22% of the reports, but its incidence level represented only 2% of the national level for this species. *Nemapogon granella* and *Attagenus* spp. were the second and third most common arthropods, representing 17% and 13% of the reports, respectively. Mites and some unidentified moths each occurred in 9% of the reports. Other less common kinds of stored-product insects from Port Colborne elevators included *Cryptolestes ferrugineus*, *C. turcicus*, *Tenebroides mauritanicus*, *Plodia interpunctella*, *Lathridius* spp., *Tenebrio obscurus*, and *Ptinus tectus*.

Renfrew, Ont.

Grain elevators in Renfrew were infested with 10 kinds of arthropods (Table 13). Of these, four kinds were more common than most others. *Attagenus* spp. was the most common insect group, occurring in 38% of the reports. Its incidence level, however, represented only 6% of the national level for this species, probably because of the small sample size of reports (21) from Renfrew. *Tenebroides mauritanicus* was the second most common kind of arthropod (14%); *Tribolium castaneum* and *Tribolium* spp. were jointly ranked third, occurring in 10% of the reports. Other less common stored-product insects appearing in the reports included *Cryptolestes ferrugineus*, *C. pusillus*, mites, *Sitophilus granarius*, *Cryptophagus* spp., and *Tribolium confusum*.

Kingston, Ont.

Grain elevators in Kingston were infested with 13 kinds of arthropods (Table 13). Only two species of stored-product insects, *Tenebrio molitor* and *Nemapogon granella*, predominated in the arthropod fauna in grain elevators. *T. molitor* was most common, occurring in 24% of the reports, but its incidence level represented only 4% of the national level for this species. *N. granella* was the second most common arthropod, occurring in 19% of the reports. Other less common arthropods, in order of their frequency of occurrence, were *Attagenus* spp., *Plodia interpunctella*, mites, unidentified moths, *Ephestia kuehniella*, Psocoptera, *Niptus unicolor, Pyralis farinalis, Ptinus* spp., *Tribolium castaneum*, and *Pselaphochernes* spp. (a pseudoscorpion).

Prescott, Ont.

Grain elevators in Prescott, from which only 18 reports were analyzed, were infested with 10 kinds of arthropods. Of these, *Nemapogon granella* was most common, occurring in 28% of the reports (Table 13). This incidence level of *N. granella* represented only 3% of the national level for this species. Mites were the second most common arthropod group, occurring in 17% of the reports. *Attagenus* spp. and *Cryptolestes ferrugineus* were the third most common arthropods, each occurring in 11% of the reports. Other less common arthropods found in Prescott elevators were *Tenebrio molitor, Cryptolestes pusillus, Plodia interpunctella, Ptinus* spp., Psocoptera, and *Tribolium castaneum*. Because of the small sample size, the variety and frequency of arthropod pests reported from this city may not be representative of the actual insects present.

Montreal, Que.

Grain elevators in Montreal were infested with 34 kinds of arthropods (Table 14). Of these, *Tenebrio molitor* was the most common arthropod species, occurring in 23% of the reports from this city. Its incidence level, however, was only 11% of the national level for this species. *Attagenus* spp. and *Nemapogon granella* were the second and third most common arthropods, occurring in 17% and 11% of the reports, respectively. The incidence level of *Attagenus* spp. in Montreal elevators represented 45% of the national level for this group of dermestid species. Other less common insects, in order of their frequency of occurrence, were *Sitophilus granarius, Cryptolestes pusillus, C. ferrugineus, S. oryzae*, and *Pyralis farinalis*. The incidence levels of *C. pusillus, S. oryzae*, and *S. granarius* were 58%, 51%, and 41% of the national levels, respectively, for these species. Some of the other still less common stored-product insect species found in Montreal elevators included *Tinea pallescentella, Tenebroides mauritanicus, Plodia interpunctella, Typhaea stercorea, Cryptolestes turcicus, Lasioderma serricorne, Haplotinea ditella*, and *Ahasverus advena*.

Table 13. Frequency of occurrence of stored-product arthropods in grain elevators in five cities in southern and eastern Ontario as a percentage of total occurrence (1969–1981)

Arthropod	Toronto $n = 84$* (%)	Percentage of Canadian reports	Port Colborne $n = 21$* (%)	Percentage of Canadian reports	Renfrew $n = 21$* (%)	Percentage of Canadian reports	Kingston $n = 37$* (%)	Percentage of Canadian reports	Prescott $n = 18$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (n)*
Tenebrio molitor	15	6	22	2	0	0	24	4	6	†	223
Nemapogon granella	6	3	17	2	0	0	19	4	28	3	186
Attagenus spp.	10	6	13	2	38	6	8	2	11	2	126
Cryptolestes ferrugineus	14	12	4	1	5	1	0	0	11	2	97
Mites	2	3	9	3	5	2	5	3	17	5	66
Sitophilus granarius	6	8	0	0	5	2	0	0	0	0	61
Cryptolestes pusillus	0	0	0	0	5	2	0	0	6	2	43
Pyralis farinalis	5	11	0	0	0	0	3	3	0	0	37
Tenebroides mauritanicus	2	6	4	3	14	8	0	0	0	0	36
Tinea pallescentella	1	3	0	0	0	0	0	0	0	0	31
Plodia interpunctella	4	11	4	4	0	0	8	11	6	4	27
Lepidoptera	0	0	9	8	0	0	5	8	0	0	24
Ephestia kuehniella	0	0	0	0	0	0	5	10	0	0	21
Ptinus spp.	1	6	0	0	0	0	3	6	6	6	16
Cryptophagus cellaris	1	7	0	0	0	0	0	0	0	0	15
Typhaea stercorea	1	7	0	0	0	0	0	0	0	0	15
Cryptophagus spp.	0	0	0	0	5	8	0	0	0	0	12
Psocoptera	1	9	0	0	0	0	5	18	6	9	11
Ptinus villiger	7	55	0	0	0	0	0	0	0	0	11
Tribolium castaneum	1	10	0	0	10	20	3	10	6	10	10
Ahasverus advena	2	22	0	0	0	0	0	0	0	0	9
Tribolium spp.	1	13	0	0	10	25	0	0	0	0	8
Tribolium confusum	2	29	0	0	5	14	0	0	0	0	7
Cryptolestes turcicus	0	0	4	17	0	0	0	0	0	0	6
Lathridius spp.	0	0	4	17	0	0	0	0	0	0	6

Oryzaephilus surinamensis	4	50	0	0	0	0	0	0	0	0	6
Ptinus ocellus	1	17	0	0	0	0	0	0	0	0	6
Pselaphochernes parvus	6	100	0	0	0	0	0	0	0	0	5
Tenebrio obscurus	0	0	4	25	0	0	0	0	0	0	4
Niptus unicolor	0	0	0	0	0	0	5	50	0	0	4
Larca granulata	1	50	0	0	0	0	0	0	0	0	2
Pselaphochernes spp.	1	50	0	0	0	0	3	50	0	0	2
Ptinus fur	1	50	0	0	0	0	0	0	0	0	2
Ptinus tectus	0	0	4	50	0	0	0	0	0	0	2

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* *n* = number of reports. Total number of reports in Canada, 1095.

† Less than 1%.

Table 14. Frequency of occurrence of stored-product arthropods in grain elevators in four cities in Quebec as a percentage of total occurrence (1969–1981)

Arthropod	Montreal $n = 335$* (%)	Percentage of Canadian reports	Trois-Rivieres $n = 97$* (%)	Percentage of Canadian reports	Sorel $n = 103$* (%)	Percentage of Canadian reports	Quebec $n = 100$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (*n*)*
Tenebrio molitor	23	11	22	9	27	13	21	9	223
Nemapogon granella	11	20	11	6	10	5	3	2	186
Attagenus spp.	17	45	8	6	15	12	9	7	126
Cryptolestes ferrugineus	7	23	7	7	9	9	5	5	97
Mites	1	6	2	3	0	0	1	2	66
Sitophilus granarius	8	41	6	10	4	7	12	20	61
Cryptolestes pusillus	8	58	7	16	3	7	0	0	43
Pyralis farinalis	5	41	1	3	3	8	6	16	37
Sitophilus oryzae	6	51	5	14	5	14	6	16	37
Tenebroides mauritanicus	3	25	8	22	1	3	6	17	36
Tinea pallescentella	4	42	4	13	7	23	0	0	31
Plodia interpunctella	2	30	2	7	3	11	0	0	27
Lepidoptera	0	0	1	4	0	0	0	0	24
Ephestia kuehniella	†	10	0	0	0	0	11	52	21
Cryptolestes spp.	1	20	2	10	5	25	7	35	20
Ptinus spp.	†	6	1	6	1	6	0	0	16
Typhaea stercorea	2	47	3	20	2	13	0	0	15
Psocoptera	†	9	0	0	0	0	0	0	11
Ahasverus advena	†	11	0	0	0	0	1	11	9
Haplotinea ditella	†	33	2	22	2	22	0	0	9
Alphitobius diaperinus	0	0	1	13	2	25	4	50	8
Tribolium spp.	†	13	0	0	0	0	3	38	8
Dermestes lardarius	†	14	0	0	0	0	0	0	7

Tribolium confusum	0	0	0	0	0	0	1	14	7
Cryptolestes turcicus	1	67	0	0	0	0	1	17	6
Lathridius spp.	†	17	0	0	0	0	0	0	6
Oryzaephilus surinamensis	†	33	0	0	0	0	0	0	6
Ptinus ocellus	0	0	0	0	0	0	2	33	6
Diptera	†	20	0	0	0	0	0	0	5
Ephestia cautella	†	40	0	0	1	20	1	20	5
Lasioderma serricorne	1	80	1	20	0	0	0	0	5
Staphylinidae	†	20	0	0	0	0	0	0	5
Tenebrio obscurus	†	25	1	25	0	0	0	0	4
Microgramme filum	†	67	1	33	0	0	0	0	3
Tinea pellionella	†	33	0	0	0	0	0	0	3
Oryzaephilus mercator	†	50	0	0	0	0	0	0	2
Ptinus fur	0	0	1	50	0	0	0	0	2
Ptinus hirtellus (= P. clavipes)	0	0	1	50	1	50	0	0	2
Ptinus tectus	†	50	0	0	0	0	0	0	2
Trogoderma spp.	†	100	0	0	0	0	0	0	2

* *n* = number of reports. Total number of reports in Canada, 1095.

† Less than 1%.

Trois Rivieres, Que.

Grain elevators in Trois Rivieres were infested with 23 kinds of arthropods (Table 14). Of these, *Tenebrio molitor* was the most common species, occurring in 22% of the reports from this city. The incidence level of *T. molitor* represented 9% of the national level for this species. The next most common species were *Nemapogon granella*, *Tenebroides mauritanicus*, *Attagenus* spp., and *Cryptolestes ferrugineus*, occurring in 11%, 8%, 8%, and 7% of the city reports, respectively. The incidence level of *T. mauritanicus* was a high 22% of the national level for this species. *Cryptolestes ferrugineus* and *C. pusillus* were the fourth most common arthropods, occurring in 7% of the reports. The incidence level of *C. pusillus* represented 16% of the national level for this species as compared with only 7% for *C. ferrugineus*.

Two other relatively common insects occurring in 5–6% of the reports were *Sitophilus oryzae* and *S. granarius*. Other less common arthropods, in order of their frequency of occurrence, included *Tinea pallescentella*, *Plodia interpunctella*, mites, *Haplotinea ditella*, *Ptinus* spp., *Pyralis farinalis*, *Alphitobius diaperinus*, *Lasioderma serricorne*, *Tenebrio obscurus*, *Microgramme filum*, and *Ptinus hirtellus*. Incidence levels of several of these stored-product insect species represented 33–50% of their respective national levels.

Sorel, Que.

Grain elevators in Sorel were infested with 18 kinds of insects (Table 14). Of these, *Tenebrio molitor* was most common, occurring in 27% of the reports from this city; its incidence level represented 13% of the national level for this species. As in several other Quebec cities, *Attagenus* spp. and *Nemapogon granella* were the second and third most common insect species occurring in 15% and 10% of the reports, respectively. Other less common kinds of insects, occurring in 5% or more of the reports, in order of their frequency of occurrence, were *Cryptolestes ferrugineus*, *Tinea pallescentella*, *Sitophilus oryzae*, and *Cryptolestes* spp. Incidence levels of these insects were 9–25% of the national levels for the respective groups. Other less common stored-product insects (1–4% incidence in reports), in order of their frequency of occurrence, were *Sitophilus granarius*, *Cryptolestes pusillus*, *Pyralis farinalis*, *Plodia interpunctella*, *Typhaea stercorea*, *Haplotinea ditella*, *Alphitobius diaperinus*, *Tenebroides mauritanicus*, *Ptinus* spp., *Ephestia cautella*, and *Ptinus hirtellus*. Incidence levels of *Ptinus hirtellus*, *A. diaperinus*, and *E. cautella* represented 50%, 25%, and 20% of the national levels, respectively, for these species.

Quebec City, Que.

Grain elevators in Quebec City were infested with 18 kinds of arthropods (Table 14). Of these, *Tenebrio molitor* was by far the most common species, occurring in 21% of the reports; its incidence level represented 9% of the national level for this species. *Sitophilus granarius* was the second most common species and *Ephestia kuehniella* the third, occurring in 12% and 11% of the reports from this city, respectively; their incidence levels, however, were 20% and 52% of the national levels, respectively. Other less common arthropods, occurring in 5–9% of the reports, in order of their frequency of occurrence, were *Attagenus* spp., *Cryptolestes* spp., *Pyralis farinalis, S. oryzae, Tenebroides mauritanicus*, and *Cryptolestes ferrugineus*. Some of the stored-product arthropods that were less common included *Alphitobius diaperinus, Ptinus ocellus*, mites, *Ahasverus advena, E. cautella, Tribolium confusum*, and *C. turcicus*. The incidence level of *Alphitobius diaperinus* from this city represented 50% of the national level for this species; the corresponding national incidence level for *P. ocellus* was 33% and for *E. cautella* 20%.

Major arthropod pests of feed mills and warehouses and their national status

Major arthropods associated with feed mills and warehouses were evident in 413 inspection reports from six cities (Tables 15 and 16). Most of the reports, 257, came from feed mills in Toronto. There was no report from any location west of Winnipeg.

Winnipeg, Man.

Feed mills in Winnipeg were infested with 12 kinds of stored-product insects (Table 15). *Tribolium confusum* and *Oryzaephilus surinamensis* were the two most common species, occurring in 23% of the reports. The incidence of *T. confusum* represented 22% of the national level for this species, whereas the incidence of *O. surinamensis* represented 63% of the national level. *Tribolium audax* was the third most common species, occurring in 17% of the reports, the only Canadian records of *T. audax* found. *Attagenus* spp. were the fourth most common kind of insect, occurring in 16% of the reports. For this species, the incidence level represents only 17% of the national level. All other kinds of insects were considerably less common, occurring in no more than 5% of the reports. These insects, in order of their frequency of occurrence, were *Tenebrio molitor*, Dermestidae, *Tribolium castaneum, Tenebroides mauritanicus, Ptinus* spp., *Anthrenus verbasci*, and *A. scrophulariae*.

Baden, Ont.

Feed mills in Baden were infested with 11 kinds of insects (Table 15). Of the four kinds of insects that were more common than most other kinds, three occurred in 19% of the reports from this location. These were *Ephestia kuehniella, Tribolium confusum*, and *Attagenus* spp. The incidence level of *E. kuehniella* represented 33% of the national level for this species. *Tenebrio molitor* was the second most common insect, occurring in 12% of the reports. Other less common insects included *Tenebroides mauritanicus, Sitophilus granarius, Pyralis farinalis, Tenebrio obscurus*, and *Cryptolestes turcicus*. The occurrence of a window fly, *Scenopinus fenestralis*, which is not a stored-product insect, may be incidental.

Table 15. Frequency of occurrence of stored-product arthropods in feed mills in one city in Manitoba and two cities in Ontario as a percentage of total occurrence (1969–1981)

Arthropod	Winnipeg, Man. $n = 75$* (%)	Percentage of Canadian reports	Baden, Ont. $n = 26$* (%)	Percentage of Canadian reports	Hamilton, Ont. $n = 39$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (*n*)*
Tribolium castaneum	3	2	0	0	3	1	82
Tribolium confusum	23	22	19	7	21	11	76
Attagenus spp.	16	17	19	7	15	8	72
Nemapogon granella	0	0	0	0	8	9	35
Tenebrio molitor	4	10	12	10	3	3	31
Oryzaephilus surinamensis	23	63	0	0	0	0	27
Tribolium spp.	3	9	0	0	0	0	22
Tenebroides mauritanicus	1	17	4	6	5	12	17
Ephestia kuehniella	0	0	19	33	0	0	15
Sitophilus granarius	0	0	4	7	0	0	15
Dermestidae	4	23	0	0	0	0	13
Tribolium audax	17	100	0	0	0	0	13
Pyralis farinalis	0	0	4	10	5	20	10
Ptinus spp.	1	13	0	0	0	0	8
Tenebrio obscurus	0	0	4	13	8	38	8
Cryptolestes turcicus	0	0	4	17	8	50	6
Cynaeus angustus	0	0	0	0	13	100	5
Anthrenus verbasci	1	33	0	0	0	0	3
Ptinus villiger	0	0	4	33	3	33	3
Anthrenus scrophulariae	1	50	0	0	0	0	2
Scenopinus fenestralis	0	0	8	100	0	0	2
Stegobium paniceum	0	0	0	0	5	100	2
Trogoderma inclusum	0	0	0	0	5	100	2

* $n =$ number of reports. Total number of reports in Canada, 413.

Hamilton, Ont.

Feed mills in Hamilton were infested with 13 kinds of insects, of which three kinds were more common than others (Table 15). *Tribolium confusum* was the most common species, occurring in 21% of the reports; its incidence level represented 11% of the national level for this species. *Attagenus* spp. were the second most common insect, occurring in 15% of the reports. *Cynaeus angustus* was the third most common insect, occurring in 13% of the reports. All Canadian reports of occurrence of this insect species in the feed mill habitat originated in Hamilton. Other less common stored-product insects, occurring in 3–8% of the reports, in order of their frequency of occurrence, were *Nemapogon granella*, *Tenebrio obscurus*, *Cryptolestes turcicus*, *Tenebroides mauritanicus*, *Stegobium paniceum*, *Trogoderma inclusum*, *Pyralis farinalis*, *Tribolium castaneum*, *Tenebrio molitor*, and *Ptinus villiger*. The incidence levels of *S. paniceum* and *Trogoderma inclusum* were 100% of the national level for these species.

Port Colborne, Ont.

Feed mills in Port Colborne were infested with 19 kinds of arthropods (Table 16). *Tribolium castaneum* was the dominant species, occurring in 36% of the reports. The incidence level of *T. castaneum* represented 55% of the national level for this species. *Attagenus* spp. were the second most common insect species group and occurred in 11% of the reports; their occurrence represented 19% of the national incidence level for these species. The other kinds of less common stored-product arthropods, occurring in 7–8% of the reports from this city, were Dermestidae, *Cryptolestes ferrugineus*, and *Plodia interpunctella*. The incidence of *C. ferrugineus* and *P. interpunctella* represented 24% and 36%, respectively, of the national levels for these species. Some of the remaining arthropods, which occurred in less than 5% of the reports, in order of their frequency of occurrence, were *Nemapogon granella*, *Tenebrio molitor*, *Oryzaephilus surinamensis*, mites, *Sitophilus granarius*, *Cryptolestes turcicus*, *C. pusillus*, and Psocoptera.

Toronto, Ont.

The arthropod fauna in feed mills in Toronto were analyzed from a set of 257 reports, which was the largest sample size from a location considered under the feed mill category (Table 16). Feed mills in this city were infested with 30 kinds of arthropods. Only four kinds of insects were common, occurring in 10–11% of the reports; these were *Tribolium confusum*, *Attagenus* spp., *Nemapogon granella*, and *Cryptolestes ferrugineus*. For the last two species the incidence level represented 74% of the national level. Less common arthropods occurring in 5% or more reports included *Tenebrio molitor*, *Tribolium castaneum*, *Plodia interpunctella*, *Tenebroides mauritanicus*, and *Gibbium psylloides*. The incidence levels of *T. mauritanicus* and *G. psylloides* represented 71% and 100%, respectively, of the national levels for these species. *Hofmannophila pseudospretella*, a moth that is common in the grain elevators of eastern and western coastal cities in Canada,

Table 16. Frequency of occurrence of stored-product arthropods in feed mills in three cities in Ontario as a percentage of total occurrence (1969–1981)

Arthropod	Port Colborne $n = 124$* (%)	Percentage of Canadian reports	Toronto $n = 257$* (%)	Percentage of Canadian reports	Almonte $n = 30$* (%)	Percentage of Canadian reports	Arthropods in Canada [ordered incidence] (*n*)*
Tribolium castaneum	36	55	5	17	17	6	82
Tribolium confusum	†	1	11	37	20	8	76
Attagenus spp.	11	19	11	40	10	4	72
Nemapogon granella	4	14	10	74	0	0	35
Cryptolestes ferrugineus	7	24	10	74	0	0	34
Tenebrio molitor	4	16	6	52	7	7	31
Oryzaephilus surinamensis	3	15	2	22	0	0	27
Plodia interpunctella	7	36	5	56	3	4	25
Tribolium spp.	0	0	3	36	23	32	22
Tenebroides mauritanicus	†	6	5	71	0	0	17
Ephestia kuehniella	0	0	2	33	0	0	15
Sitophilus granarius	2	20	4	67	3	7	15
Dermestidae	8	77	0	0	0	0	13
Gibbium psylloides	0	0	5	100	0	0	12
Mites	3	36	2	36	10	27	11
Pyralis farinalis	†	10	2	60	0	0	10
Ptinus spp.	0	0	3	38	0	0	8
Cryptolestes pusillus	2	33	0	0	0	0	6
Cryptolestes turcicus	2	50	†	50	0	0	4
Hofmannophila pseudospretella	0	0	2	100	0	0	4
Typhaea stercorea	0	0	†	50	0	0	4

Anthrenus verbasci	†	33	†	33	0	0	3
Diptera	0	0	†	67	0	0	3
Pselaphochernes parvus	0	0	1	100	0	0	3
Psocoptera	2	67	†	33	0	0	3
Ptinus raptor	0	0	†	67	3	33	3
Ptinus villiger	0	0	†	33	0	0	3
Ahasverus advena	0	0	†	50	0	0	2
Alphitobius diaperinus	0	0	†	50	3	50	2
Anthrenus scrophulariae	†	50	0	0	0	0	2
Cryptolestes spp.	0	0	2	†	0	0	2
Dermestes lardarius	†	50	1	†	0	0	2
Ptinus ocellus	0	0	2	†	0	0	2

[*] *n* = number of reports. Total number of reports in Canada, 413.

† Less than 1%.

occurred in 2% of the reports from Toronto feed mills, representing the only reoccurrence of this species found in flour mills. Some of the following arthropods also occurred occasionally: *Oryzaephilus surinamensis*, *Ptinus* spp., mites, *Ephestia kuehniella*, *Pyralis farinalis*, *Ptinus ocellus*, *Dermestes lardarius*, *Typhaea stercorea*, *Ptinus villiger*, *Ahasverus advena*, and *Alphitobius diaperinus*.

Almonte, Ont.

Feed mills of Almonte were infested with 10 kinds of arthropods (Table 16). One-half of the arthropods were more common than others. *Tribolium* spp. were the most common kind of arthropod, occurring in 23% of the reports. *Tribolium confusum* was the second most common arthropod species, and *T. castaneum* the third. Next in frequency of occurrence were *Attagenus* spp. and mites, which occurred in 10% of the reports. Somewhat less common species, with 3–7% incidence levels, included *Tenebrio molitor*, *Sitophilus granarius*, *Plodia interpunctella*, *Ptinus raptor*, and *Alphitobius diaperinus*.

Regional ranking and seasonal occurrence of stored-products arthropods

Flour mill category

British Columbia

Tribolium confusum ranked first among the arthropods occurring in flour mills in British Columbia (Table 17). *T. confusum* was most common in spring and was progressively less so in winter, summer, and autumn. Other storage species of the genus *Tribolium* occurred most frequently in autumn and least in summer; none occurred in spring.

Prairie Provinces

Tribolium confusum ranked first among the arthropods in flour mills in the Prairie Provinces; 64% of all infestations in this region involved *T. confusum* (Table 18). It was common in all four seasons, with frequency levels ranging between 69% in winter and 56% in spring. Other species of *Tribolium*—the second-ranking arthropod group—also occurred in all seasons with a similar seasonal occurrence pattern. *Trogoderma inclusum* and *Attagenus* spp. were the next most common stored-grain pests. Although these species occurred in all seasons, they were most common in spring. Seven other kinds of arthropods occurred only sporadically when records of single occurrences were excluded from the analysis (Table 18). Their frequency of occurrence was too low to develop specific patterns.

Table 17. Frequency of occurrence and rank of stored-product arthropods in flour mills in British Columbia during four seasons (1969–1981)

		Occurrence				
Rank	Arthropod*	Total $n = 23$† (%)	Summer $n = 7$† (%)	Autumn $n = 8$† (%)	Winter $n = 6$† (%)	Spring $n = 2$† (%)
1	*Tribolium confusum*	64	57	38	67	100
2	*Tribolium* spp.	10	14	25	17	0

* Arthropod categories with a single record of occurrence are omitted.

† $n =$ number of reports.

Table 18. **Frequency of occurrence and rank of stored-product arthropods in flour mills in the Prairie Provinces during four seasons (1969–1981)**

		Occurrence				
Rank	Arthropod*	Total $n = 182$† (%)	Summer $n = 34$† (%)	Autumn $n = 54$† (%)	Winter $n = 42$† (%)	Spring $n = 52$† (%)
1	*Tribolium confusum*	64	68	67	69	56
2	*Tribolium* spp.	10	12	13	14	4
3	*Trogoderma inclusum*	6	6	6	2	10
4	*Attagenus* spp.	6	6	2	5	10
5	*Tribolium castaneum*	3	0	2	2	6
6	*Sitophilus oryzae*	1	0	2	0	2
7	*Ephestia kuehniella*	1	3	0	0	2
8	*Lepisma saccharina*	1	0	0	2	2
9	*Ptinus villiger*	1	0	2	0	2
10	Dermestidae	1	0	4	0	0
11	*Tenebroides mauritanicus*	1	3	0	2	0

* Arthropod categories with a single record of occurrence are omitted.

† $n =$ number of reports.

Ontario

Tribolium confusum and *T. castaneum* ranked as first and second, respectively, among the 37 kinds of arthropods (excluding single-occurrence records) occurring in flour mills in Ontario (Table 19). The most commonly occurring arthropods were present in all four seasons, but levels of their frequency of occurrence varied. *T. confusum* was most common in winter and least in summer and spring, whereas *T. castaneum* was most common in spring and least in summer. Of the three kinds of insects that were the third most common in Ontario flour mills, *Attagenus* spp. were most common in summer and spring and least in autumn and winter; *Gibbium psylloides* was most common in winter and least in autumn; and *Tribolium* spp. were most common in autumn and least in summer and spring. Other less common kinds of flour mill arthropods occurred with relatively low frequencies (1–7%) in each season. *Tenebrio molitor* was most common in summer, *Sitophilus granarius* in autumn, and *Cryptolestes ferrugineus* in winter. *Ephestia kuehniella*, *Ptinus* spp., and *Tenebroides mauritanicus* were most common in spring.

Quebec

Tribolium castaneum ranked first among the 19 arthropods (excluding single-occurrence records) occurring in flour mills in Quebec (Table 20). Although *T. castaneum* occurred in more than 52% of the reports, it was most common in winter, with a 75% frequency of occurrence. The second most common arthropod species on a year-round basis, *Sitophilus granarius*, occurred only in 7% of the reports from Quebec flour mills, and was least common in winter. However, *Sitophilus oryzae*, the third most common species, was most common in winter and least in summer. Of the remaining flour mill arthropods, *Attagenus* spp. were most common in spring and least in winter; *Tenebrio molitor* was most common in spring and least in autumn; *Cryptolestes ferrugineus* was most common in autumn and least in winter; *C. pusillus* was most common in summer and least in winter; and *Tenebroides mauritanicus* was most common in summer and autumn and least in spring, with none occurring in winter. It appears that the most preferred season for various species in Quebec flour mills was as follows: *Tribolium confusum*, winter; *Trogoderma* spp., spring; *Oryzaephilus surinamensis*, autumn; and *Pyralis farinalis*, summer.

Maritime Provinces

Tribolium spp. were the only arthropods that occurred in flour mills in the Maritime Provinces (excluding single-incidence records) (Table 21). Undetermined species (probably both *T. confusum* and *T. castaneum*) of this genus occurred in more than 50% of reports in each season. *Tribolium destructor* was most common in spring and least in winter; it did not occur in summer. *T. castaneum* was most common in autumn. Because of small numbers of reports from the flour mills of this region, seasonal incidence patterns of various species may not be too meaningful.

Table 19. Frequency of occurrence and rank of stored-product arthropods in flour mills in Ontario during four seasons (1969–1981)

		Occurrence				
Rank	Arthropod*	Total $n = 580$† (%)	Summer $n = 162$† (%)	Autumn $n = 149$† (%)	Winter $n = 136$† (%)	Spring $n = 133$† (%)
1	*Tribolium confusum*	16	14	17	21	15
2	*Tribolium castaneum*	11	9	10	12	14
3	*Attagenus* spp.	7	9	5	6	9
4	*Gibbium psylloides*	7	6	5	10	8
5	*Tribolium* spp.	7	5	10	7	5
6	*Ptinus* spp.	5	8	3	3	7
7	*Tenebrio molitor*	5	7	5	1	6
8	*Sitophilus granarius*	4	4	6	2	5
9	*Cryptolestes pusillus*	4	4	4	4	5
10	*Cryptolestes ferrugineus*	4	3	5	6	2
11	*Ephestia kuehniella*	3	4	4	2	5
12	*Tenebroides mauritanicus*	3	3	3	3	5
13	Dermestidae	2	2	2	3	3
14	*Oryzaephilus surinamensis*	2	1	1	4	2
15	*Nemapogon granella*	2	1	3	2	0
16	*Trogoderma inclusum*	1	3	1	0	1
17	*Cryptolestes turcicus*	1	1	1	2	2
18	Mites	1	1	1	2	0
19	*Typhaea stercorea*	1	3	1	0	0
20	Psocoptera	1	1	1	2	0
21	*Dermestes lardarius*	1	1	1	1	2
22	*Plodia interpunctella*	1	1	1	2	0
23	*Pyralis farinalis*	1	2	1	0	0
24	*Haplotinea ditella*	1	0	1	2	0

25	Sowbugs	1	1	1	0	0
26	*Anthrenus verbasci*	1	1	0	0	2
27	*Ptinus villiger*	1	1	0	2	0
28	*Mezium americanum*	1	0	0	1	2
29	*Ahasverus advena*	1	1	1	0	0
30	*Cynaeus angustus*	1	0	1	0	0
31	*Anthicus floralis*	1	1	1	0	0
32	*Cryptophagus* spp.	0	0	1	1	0
33	Diptera	0	1	1	0	0
34	*Anthrenus scrophulariae*	0	0	1	0	0
35	*Ptinus tectus*	0	1	0	0	1
36	*Ptinus ocellus*	0	1	0	1	0
37	*Tenebrio obscurus*	0	1	0	0	1

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* Arthropod categories with a single record of occurrence are omitted.

† *n* = number of reports.

Table 20. **Frequency of occurrence and rank of stored-product arthropods in flour mills in Quebec during four seasons (1969–1981)**

		Occurrence				
Rank	Arthropod*	Total $n = 374$† (%)	Summer $n = 109$† (%)	Autumn $n = 113$† (%)	Winter $n = 76$† (%)	Spring $n = 76$† (%)
1	*Tribolium castaneum*	59	55	52	75	59
2	*Sitophilus granarius*	7	9	7	1	8
3	*Sitophilus oryzae*	4	2	5	8	3
4	*Attagenus* spp.	4	5	2	1	7
5	*Tenebrio molitor*	4	5	1	3	7
6	*Cryptolestes ferrugineus*	2	2	4	1	3
7	*Cryptolestes pusillus*	2	4	2	1	3
8	*Tenebroides mauritanicus*	2	4	4	0	1
9	*Tribolium confusum*	2	1	3	5	0
10	*Trogoderma* spp.	2	1	1	1	5
11	*Tribolium* spp.	1	1	4	0	0
12	*Oryzaephilus surinamensis*	1	0	4	1	0
13	*Ephestia kuehniella*	1	1	2	0	1
14	*Alphitobius diaperinus*	1	1	1	0	3
15	*Ahasverus advena*	1	1	2	1	0
16	*Typhaea stercorea*	1	2	2	0	0
17	*Cryptophagus* spp.	1	1	1	0	1
18	*Pyralis farinalis*	1	3	0	0	0
19	*Ptinus hirtellus* (= *P. clavipes*)	1	0	3	0	0

* Arthropod categories with a single record of occurrence are omitted.

† n = number of reports.

Table 21. Frequency of occurrence and rank of stored-product arthropods in flour mills in the Maritime Provinces during four seasons (1969–1981)

		Occurrence				
Rank	Arthropod*	Total $n=27$† (%)	Summer $n=3$† (%)	Autumn $n=11$† (%)	Winter $n=9$† (%)	Spring $n=4$† (%)
1	*Tribolium* spp.	59	67	55	67	50
2	*Tribolium destructor*	19	0	18	11	50
3	*Tribolium castaneum*	11	0	18	11	0

* Arthropod categories with a single record of occurrence are omitted.

† $n=$ number of reports.

Grain elevator category

British Columbia

Of the 19 kinds of arthropods in grain elevators at Vancouver and Prince Rupert, stored-grain moths ranked at the top two positions (Table 22). *Hofmannophila pseudospretella* occurred in 16% of the all-year reports and *Endrosis sarcitrella* in 12% of the reports. *H. pseudospretella* was most common in spring and least in summer and autumn. *E. sarcitrella*, however, was most common in winter and least in spring. *Tenebrio molitor*, which was the third most common year-round arthropod, was most common in spring and occurred with equal frequency in the other three seasons. The fourth-ranking arthropod group, Lepidoptera spp. (moths), likely represented unidentified specimens of *H. pseudospretella* and *E. sarcitrella*. The most preferred season or seasons for the other less common but economically important arthropod species in British Columbia grain elevators were as follows: *Ptinus* spp., winter; *Cryptolestes ferrugineus*, summer; mites, autumn and winter; *Sitophilus granarius*, spring; Psocoptera, winter; *Tribolium castaneum*, summer; *T. confusum*, spring; *Pyralis farinalis*, summer; *Attagenus* spp., spring; and *Niptus unicolor*, spring.

Thunder Bay, Ont.

Nemapogon granella was the first among the nine kinds of arthropods (excluding single-incidence records) occurring annually in the terminal elevators in Thunder Bay (Table 23). *N. granella*, which occurred in 14% or more reports in each season, was most common in winter and least in summer. *Tenebrio molitor* was the second most common arthropod, and mites the third. *T. molitor* was more common in winter and summer than in spring and autumn. Mites were more common in summer and autumn than in spring; they did not occur in winter. *Cryptolestes ferrugineus* occurred in 10% of the reports annually and was most common in autumn and least in summer. Unidentified moths were more common in summer and winter than in autumn and spring. Fungus beetles, *Cryptophagus* spp., were most common in winter and least in summer.

Ontario

As in the Thunder Bay elevators, *Nemapogon granella*, *Tenebrio molitor*, and *Cryptolestes ferrugineus* were the top three stored-product arthropods in elevators in other locations in Ontario (Table 24). *N. granella* occurred in 13% or more reports in each season, with autumn being its most preferred season. *T. molitor* was far more common in summer than in any other season; its seasonal frequency was lowest in winter. *C. ferrugineus* was most common in winter and least in spring and summer. *Attagenus* spp., the fourth most common arthropods, were more common in spring and summer than in autumn. Mites occurred in all seasons, but with relatively low frequency in winter. The most preferred season for some of the other less common insect species was as follows: *Plodia interpunctella*, winter; *Sitophilus granarius*, autumn; *Ptinus villiger*, spring; *Tribolium castaneum*, winter; and *Cryptolestes pusillus*, winter.

Table 22. Frequency of occurrence and rank of stored-product arthropods in grain elevators in British Columbia during four seasons (1969–1981)

		Occurrence				
Rank	Arthropod*	Total $n = 103$† (%)	Summer $n = 48$† (%)	Autumn $n = 24$† (%)	Winter $n = 13$† (%)	Spring $n = 18$† (%)
1	*Hofmannophila pseudospretella*	16	13	13	15	28
2	*Endrosis sarcitrella*	12	13	13	15	6
3	*Tenebrio molitor*	9	8	8	8	11
4	Lepidoptera	6	2	17	8	0
5	*Ptinus* spp.	6	6	4	8	6
6	*Cryptolestes ferrugineus*	5	8	4	0	0
7	Mites	5	2	8	8	6
8	*Sitophilus granarius*	4	2	0	8	11
9	Staphylinidae spp.	4	4	8	0	0
10	*Tinea pallescentella*	3	4	4	0	0
11	Psocoptera	3	0	4	8	6
12	*Cryptophagus cellaris*	3	4	0	8	0
13	*Tribolium castaneum*	2	4	0	0	0
14	*Tribolium confusum*	2	2	0	0	6
15	*Cryptolestes* spp.	2	0	4	8	0
16	*Pyralis farinalis*	2	4	0	0	0
17	*Attagenus* spp.	2	2	0	0	6
18	*Niptus unicolor*	2	2	0	0	6
19	*Cryptophagus* spp.	2	0	4	0	6

* Arthropod categories with a single record of occurrence are omitted.

† $n =$ number of reports.

Table 23. **Frequency of occurrence and rank of stored-product arthropods in grain elevators in Thunder Bay, Ont., during four seasons (1969–1981)**

		Occurrence				
Rank	Arthropod*	Total $n = 98$† (%)	Summer $n = 29$† (%)	Autumn $n = 50$† (%)	Winter $n = 8$† (%)	Spring $n = 11$† (%)
1	*Nemapogon granella*	24	14	26	38	27
2	*Tenebrio molitor*	13	24	6	25	9
3	Mites	12	14	14	0	9
4	*Cryptolestes ferrugineus*	10	3	14	13	9
5	Lepidoptera	9	14	6	13	9
6	*Cryptophagus cellaris*	7	3	10	0	9
7	*Cryptophagus* spp.	7	3	8	13	9
8	*Attagenus* spp.	5	7	2	0	18
9	*Lathridius* spp.	2	3	2	0	0

* Arthropod categories with a single record of occurrence are omitted.

† $n =$ number of reports.

Table 24. Frequency of occurrence and rank of stored-product arthropods in grain elevators in Ontario during four seasons (1969–1981)

		Occurrence				
Rank	Arthropod*	Total $n=393$† (%)	Summer $n=123$† (%)	Autumn $n=180$† (%)	Winter $n=36$† (%)	Spring $n=54$† (%)
1	*Nemapogon granella*	16	14	19	17	13
2	*Tenebrio molitor*	16	24	12	11	15
3	*Cryptolestes ferrugineus*	11	7	13	22	7
4	*Attagenus* spp.	8	12	4	11	13
5	Mites	7	7	8	3	6
6	Lepidoptera	4	5	3	3	4
7	*Plodia interpunctella*	3	4	3	6	0
8	*Cryptophagus cellaris*	3	2	4	3	4
9	*Tenebroides mauritanicus*	3	4	2	0	2
10	*Sitophilus granarius*	2	0	5	0	0
11	*Pyralis farinalis*	2	2	3	0	2
12	*Ptinus villiger*	2	1	1	3	7
13	*Cryptophagus* spp.	2	1	3	3	2
14	*Tribolium castaneum*	2	2	1	6	2
15	*Cryptolestes pusillus*	2	1	2	3	0
16	*Ephestia kuehniella*	2	1	2	0	2
17	Psocoptera	1	2	2	0	0
18	*Pselaphochernes parvus*	1	2	1	0	4
19	*Ptinus* spp.	1	0	2	3	2
20	*Lathridius* spp.	1	2	1	0	0
21	*Tribolium confusum*	1	0	1	3	2

Table 24. Frequency of occurrence and rank of stored-product arthropods in grain elevators in Ontario during four seasons (1969–1981) *(concluded)*

		Occurrence				
Rank	Arthropod*	Total $n = 393$† (%)	Summer $n = 123$† (%)	Autumn $n = 180$† (%)	Winter $n = 36$† (%)	Spring $n = 54$† (%)
22	*Oryzaephilus surinamensis*	1	0	2	0	0
23	*Tinea pallescentella*	1	2	1	0	0
24	*Ahasverus advena*	1	1	2	0	0
25	*Tribolium* spp.	1	0	0	6	2
26	*Typhaea stercorea*	1	2	1	0	0
27	*Haplotinea ditella*	1	1	0	0	2
28	Diptera	1	1	0	0	2
29	*Pselaphochernes* spp.	1	1	1	0	0
30	*Ptinus ocellus*	1	0	1	0	0
31	*Niptus unicolor*	1	0	1	0	0

* Arthropod categories with a single record of occurrence are omitted.

† $n =$ number of reports.

Quebec

Tenebrio molitor, Attagenus spp., and *Nemapogon granella* were the top three among the 31 stored-product arthropods in the terminal elevators in Quebec (Table 25). *T. molitor*, the most common species, occurred in 15% or more reports in each season; its seasonal frequency of occurrence was high in summer and spring and low in autumn. *Attagenus* spp. occurred in 28% of the reports in spring and only in 6% of the reports in winter. *N. granella* occurred in 10–11% of the reports in all seasons except in spring, when it occurred in only 3% of the samples. *Sitophilus granarius*, the fourth ranked arthropod, was common in autumn and winter and less so in spring. *Cryptolestes ferrugineus*, which was as numerous as *S. granarius*, was most common in winter and relatively scarce in summer. *Sitophilus oryzae*, the fifth-ranked species, was most common in autumn and least in spring. *Cryptolestes pusillus* occurred in 5% of the reports from Quebec elevators; it was most common in winter and least in summer. The most preferred season for some of the other relatively less common arthropods in Quebec elevators was as follows: *Pyralis farinalis*, spring; *Tenebroides mauritanicus*, winter; *Tinea pallescentella*, autumn; *Ephestia kuehniella*, summer; *Typhaea stercorea*, autumn; *Haplotinea ditella*, spring; *Alphitobius diaperinus*, spring; and *Lasioderma serricorne* and *Ahasverus advena*, winter. Because the total number of reports from Quebec elevators was sizable (644), these generalizations about seasonal arthropod incidence patterns are likely to be reliable.

Maritime Provinces

Nemapogon granella was the most common among the 17 kinds of arthropods occurring in terminal elevators in the Maritimes (Table 26). *N. granella* occurred in 37% of the year-round reports and 53% of the spring reports; its lowest frequency of occurrence was in summer. *Tenebrio molitor* and mites were the second and third most common kinds of arthropods, respectively. *T. molitor* occurred in 12% or more of reports in each season, but it was most common in spring and least in winter. Mites occurred evenly at 16% in all seasons except in spring, when their incidence level was slightly lower than that of other seasons. *Hofmannophila pseudospretella* was the fourth most common arthropod in maritime elevators; it was most common in winter and least in autumn. Occurring only in two seasons, *Cryptolestes ferrugineus* was more common in autumn than in winter. The most preferred season for some of the other arthropods that were relatively less common was as follows: *Dermestes lardarius*, summer; *Tineola bisselliella*, summer; *Ptinus villiger*, autumn; *Pyralis farinalis*, spring; *Niptus hololeucus*, winter; and *Ahasverus advena*, winter.

Table 25. **Frequency of occurrence and rank of stored-product arthropods in grain elevators in Quebec during four seasons (1969–1981)**

Rank	Arthropod*	Occurrence				
		Total $n = 644$† (%)	Summer $n = 215$† (%)	Autumn $n = 323$† (%)	Winter $n = 35$† (%)	Spring $n = 71$† (%)
1	*Tenebrio molitor*	19	24	15	20	23
2	*Attagenus* spp.	14	16	10	6	28
3	*Nemapogon granella*	10	10	11	11	3
4	*Sitophilus granarius*	7	5	10	9	3
5	*Cryptolestes ferrugineus*	7	3	9	11	6
6	*Sitophilus oryzae*	6	5	7	3	1
7	*Cryptolestes pusillus*	5	3	7	11	6
8	*Pyralis farinalis*	4	5	3	3	9
9	*Tenebroides mauritanicus*	4	3	4	11	1
10	*Tinea pallescentella*	4	3	5	0	3
11	*Cryptolestes* spp.	3	2	4	0	0
12	*Ephestia kuehniella*	2	4	2	0	1
13	*Plodia interpunctella*	2	2	2	3	3
14	*Typhaea stercorea*	2	2	3	0	0
15	Mites	1	2	1	0	1
16	*Haplotinea ditella*	1	1	1	0	3
17	*Alphitobius diaperinus*	1	1	1	0	3
18	*Cryptolestes turcicus*	1	1	1	0	1
19	*Lasioderma serricorne*	1	1	0	6	0
20	*Ephestia cautella*	1	1	1	0	0
21	*Tribolium* spp.	1	1	0	0	1

22	*Ptinus* spp.	1	1	0	0	0
23	*Microgramme filum*	1	1	1	0	0
24	*Oryzaephilus surinamensis*	0	0	1	0	0
25	Lepidoptera	0	1	0	0	0
26	Diptera	0	1	0	0	0
27	*Trogoderma* spp.	0	0	0	0	1
28	*Ptinus hirtellus* (=*P. clavipes*)	0	0	1	0	0
29	*Ptinus ocellus*	0	1	0	0	0
30	*Tenebrio obscurus*	0	1	0	0	0
31	*Ahasverus advena*	0	0	0	3	0

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* Arthropod categories with a single record of occurrence are omitted.

† n = number of reports.

Table 26. **Frequency of occurrence and rank of stored-product arthropods in grain elevators in the Maritime Provinces during four seasons (1969–1981)**

		Occurrence				
Rank	Arthropod*	Total $n = 167$† (%)	Summer $n = 69$† (%)	Autumn $n = 58$† (%)	Winter $n = 25$† (%)	Spring $n = 15$† (%)
1	*Nemapogon granella*	37	29	38	44	53
2	*Tenebrio molitor*	17	17	17	12	20
3	Mites	16	16	16	16	13
4	*Hofmannophila pseudospretella*	6	7	3	8	7
5	*Cryptolestes ferrugineus*	4	0	9	4	0
6	*Dermestes lardarius*	3	4	3	0	0
7	*Tineola bisselliella*	2	4	0	0	0
8	*Ptinus villiger*	2	0	5	0	0
9	*Pyralis farinalis*	1	1	0	0	7
10	*Tinea pellionella*	1	1	2	0	0
11	Lepidoptera	1	3	0	0	0
12	Psocoptera	1	1	2	0	0
13	*Ptinus* spp.	1	1	2	0	0
14	*Ptinus ocellus*	1	1	2	0	0
15	*Niptus hololeucus*	1	0	2	4	0
16	*Ahasverus advena*	1	0	0	8	0
17	*Cryptophagus* spp.	1	3	0	0	0

* Arthropod categories with a single record of occurrence are omitted.

† n = number of reports.

Feed mill category

Prairie Provinces

Three out of nine kinds of insects occurring on a year-round basis in prairie feed mills, in order of their frequency of occurrence, were *Tribolium confusum*, *Oryzaephilus surinamensis*, and *Tribolium audax* (Table 27). *T. confusum* was generally common in all seasons except summer; it was most common in autumn. *O. surinamensis* was most common in winter and least in spring. *T. audax* was more common in spring than in any other season; its frequency level remained above 11% in every season of the year. *Attagenus* spp. were more common in spring and summer than in autumn and were not reported in winter. *Tribolium* spp. were most common in winter and were not reported in spring. The most preferred season or seasons for some of the less common kinds of insects in prairie feed mills were as follows: *Tribolium castaneum* and *Tenebrio molitor*, summer; Dermestidae, summer and winter; and *Ephestia kuehniella*, spring.

Ontario

Tribolium castaneum was first among the 37 arthropods (excluding single records of a species) that occurred annually in Ontario feed mills (Table 28). *T. castaneum* occurred in 14% of the reports annually, with the highest frequency in winter and lowest in summer. *Attagenus* spp., the second most common arthropod group, were most common in spring and least in winter. *Tribolium confusum*, which was the third most common species, was most common in winter and least in summer. *Nemapogon granella* and *Cryptolestes ferrugineus* were the fourth and fifth most common species, each occurring in 7% of the reports annually. *N. granella* was most common in summer and least in winter. *C. ferrugineus* was most common in winter and least in spring and summer. Two other relatively common species in feed mills were *Tenebrio molitor* and *Plodia interpunctella*. *T. molitor* was most common in summer and least in autumn and winter. *P. interpunctella*, however, was more common in autumn and winter than in spring. Most of the other relatively less common kinds of arthropods (with 1–3% annual occurrence reports) occurred more or less uniformly in most of the four seasons. These arthropods were most common in the following seasons: *Tenebroides mauritanicus*, summer; *Tribolium* spp., winter and spring; *Sitophilus granarius*, autumn and winter; *Ephestia kuehniella*, summer and autumn; *Gibbium psylloides*, spring; mites, summer; *Oryzaephilus surinamensis*, autumn; *Pyralis farinalis*, summer; Dermestidae, winter; and *Ptinus* spp. and *Cryptolestes pusillus*, spring.

Table 27. Frequency of occurrence and rank of stored-product arthropods in feed mills in the Prairie Provinces during four seasons (1969–1981)

Rank	Arthropod*	Occurrence				
		Total $n = 91$† (%)	Summer $n = 18$† (%)	Autumn $n = 38$† (%)	Winter $n = 16$† (%)	Spring $n = 19$† (%)
1	*Tribolium confusum*	24	6	32	25	26
2	*Oryzaephilus surinamensis*	19	17	21	31	5
3	*Tribolium audax*	14	11	13	13	21
4	*Attagenus* spp.	13	22	11	0	21
5	*Tribolium* spp.	8	11	3	25	0
6	*Tribolium castaneum*	4	11	5	0	0
7	*Tenebrio molitor*	4	11	3	0	5
8	Dermestidae	3	6	3	6	0
9	*Ephestia kuehniella*	2	0	3	0	5

* Arthropod categories with a single record of occurrence are omitted.

† $n =$ number of reports.

Table 28. Frequency of occurrence and rank of stored-product arthropods in feed mills in Ontario during four seasons (1969–1981)

		Occurrence				
Rank	Arthropod*	Total $n = 494$† (%)	Summer $n = 167$† (%)	Autumn $n = 134$† (%)	Winter $n = 84$† (%)	Spring $n = 109$† (%)
1	*Tribolium castaneum*	14	9	16	19	14
2	*Attagenus* spp.	12	12	10	6	19
3	*Tribolium confusum*	11	5	14	18	10
4	*Nemapogon granella*	7	10	6	4	6
5	*Cryptolestes ferrugineus*	7	5	8	12	5
6	*Tenebrio molitor*	6	8	4	4	6
7	*Plodia interpunctella*	5	5	6	6	3
8	*Tenebroides mauritanicus*	3	5	2	2	3
9	*Tribolium* spp.	3	1	3	5	5
10	*Sitophilus granarius*	3	2	4	4	3
11	*Ephestia kuehniella*	2	3	3	1	2
12	*Gibbium psylloides*	2	3	1	2	4
13	Mites	2	4	1	2	1
14	*Oryzaephilus surinamensis*	2	2	4	0	2
15	*Pyralis farinalis*	2	4	2	1	1
16	Dermestidae	2	1	2	4	3
17	*Tenebrio obscurus*	2	2	2	1	1
18	*Ptinus* spp.	1	1	1	1	4
19	*Cryptolestes turcicus*	1	2	1	2	0
20	*Cynaeus angustus*	1	1	2	0	0
21	*Cryptolestes pusillus*	1	0	1	0	3
22	*Hofmannophila pseudospretella*	1	2	0	0	1

Table 28. **Frequency of occurrence and rank of stored-product arthropods in feed mills in Ontario during four seasons (1969–1981)** *(concluded)*

Rank	Arthropod*	Occurrence				
		Total $n = 494$† (%)	Summer $n = 167$† (%)	Autumn $n = 134$† (%)	Winter $n = 84$† (%)	Spring $n = 109$† (%)
23	Psocoptera	1	1	1	0	0
24	*Pselaphochernes parvus*	1	0	1	0	2
25	*Ptinus villiger*	1	1	1	0	1
26	*Ptinus raptor*	1	1	0	0	1
27	*Typhaea stercorea*	1	1	0	1	0
28	*Cryptolestes* spp.	‡	0	1	1	0
29	*Scenopinus fenestralis*	‡	1	1	0	0
30	Diptera	‡	1	0	1	0
31	*Trogoderma inclusum*	‡	1	0	0	0
32	*Anthrenus verbasci*	‡	0	2	0	0
33	*Ptinus ocellus*	‡	1	0	1	0
34	*Alphitobius diaperinus*	‡	1	1	0	0
35	*Dermestes lardarius*	‡	1	1	0	0
36	*Ahasverus advena*	‡	0	2	0	0
37	*Stegobium paniceum*	‡	1	0	0	0

* Arthropod categories with a single record of occurrence are omitted.

† $n =$ number of reports.

‡ Less than 1%.

Quebec

Only one species, *Tribolium castaneum*, was reported from Quebec feed mills, which were represented by only 14 reports. *T. castaneum* occurred in 79% of the reports annually. Seasonal distribution of its frequency was as follows: spring, 100%; summer and autumn, 75%; and winter, 50%. Other species that occurred may have been missed because of the small number of reports.

Combined regional occurrences of arthropods

Two or more kinds of arthropods are often found together in flour mills, grain elevators, and feed mills. Such combined occurrences usually indicate that more than one kind of arthropod favor and share a similar ecological niche with a certain combination of temperature, relative humidity, and food type. Whether such combined occurrences imply interdependence among arthropod species, a stage of their ecological succession, or a function of their high frequency of occurrence in a mill or grain elevator is not known. The following brief analysis of such associations will help future investigation of specific problems of pest management with the aid of insecticides or nonchemical methods.

The highest frequency of association among arthropod species, regardless of their granary habitat or geographical location, was found in 34% of the reports and included three kinds of insects—*Tenebrio molitor, Attagenus* spp., and *Nemapogon granella* (Table 29); this combination was more common in eastern Canadian grain elevators than elsewhere. The second highest frequency of association, 22%, occurred between *T. molitor* and *N. granella*, and between *T. molitor* and *Attagenus* spp. Other combined occurrences with 10% or higher frequency of association were as follows: *Tribolium* spp. and *Attagenus* spp.; *N. granella* and *Attagenus* spp.; *Tenebrio molitor, Attagenus* spp., and *Tribolium confusum*; *T. castaneum, Attagenus* spp., and *T. confusum*; and *N. granella, Attagenus* spp., and *T. confusum*. Several other combinations of the above-mentioned kinds of insects were also found with 3–9% frequency of association (Table 29).

Flour mill category

Ontario

The two most common associations of two kinds of insects in Ontario flour mills were between *Tribolium confusum* and *Attagenus* spp., and between *T. confusum* and *Gibbium psylloides*; both pairs had 27% frequency of association (Table 30). The second most common association occurred between *T. castaneum* and *Attagenus* spp., and the third between *T. castaneum* and *G. psylloides*. Five other associations that included two kinds of insects also occurred with various combinations of the same species or species groups.

The most common association of three kinds of insects (frequency of association 60%, Table 30) occurred among *T. confusum, Attagenus* spp., and *G. psylloides*. *T. confusum* and *T. castaneum* occurred together, with 4% frequency of association. They also occurred in a three-kind combination with *Attagenus* spp., which had a 20% occurrence.

Table 29. Frequency of association of the most common stored-product arthropods in flour mills, grain elevators, and feed mills in Canada (1969–1981)

Arthropods					Frequency of association (%*)
Tenebrio molitor	+	*Nemapogon granella*			22
Tenebrio molitor	+	*Attagenus* spp.			22
Tribolium spp.	+	*Attagenus* spp.			13
Nemapogon granella	+	*Attagenus* spp.			12
Tribolium castaneum	+	*Attagenus* spp.			9
Tribolium castaneum	+	*Tribolium confusum*			5
Tribolium castaneum	+	*Nemapogon granella*			4
Tenebrio molitor	+	*Tribolium confusum*			4
Tenebrio molitor	+	*Tribolium castaneum*			4
Tribolium confusum	+	*Nemapogon granella*			3
Tenebrio molitor	+	*Attagenus* spp.	+	*Nemapogon granella*	34
Tenebrio molitor	+	*Attagenus* spp.	+	*Tribolium confusum*	11
Tribolium castaneum	+	*Attagenus* spp.	+	*Tribolium confusum*	10
Nemapogon granella	+	*Attagenus* spp.	+	*Tribolium confusum*	10
Nemapogon granella	+	*Attagenus* spp.	+	*Tribolium castaneum*	9
Tenebrio molitor	+	*Attagenus* spp.	+	*Tribolium castaneum*	7
Tenebrio molitor	+	*Nemapogon granella*	+	*Tribolium castaneum*	7
Tribolium confusum	+	*Nemapogon granella*	+	*Tribolium castaneum*	5
Tribolium confusum	+	*Nemapogon granella*	+	*Tenebrio molitor*	4
Tribolium confusum	+	*Tenebrio molitor*	+	*Tribolium castaneum*	3

* Percentages are based on the total number of occurrences for combinations of two ($n = 486$) and three ($n = 122$) arthropods; $n =$ number of arthropods.

Table 30. Frequency of association of the most common stored-product arthropods in flour mills in Ontario (1969–1981)

Arthropods					Frequency of association (%*)
Tribolium confusum	+	*Attagenus* spp.			27
Tribolium confusum	+	*Gibbium psylloides*			27
Tribolium castaneum	+	*Attagenus* spp.			14
Tribolium castaneum	+	*Gibbium psylloides*			9
Tribolium spp.	+	*Attagenus* spp.			7
Gibbium psylloides	+	*Attagenus* spp.			6
Tribolium castaneum	+	*Tribolium confusum*			4
Tribolium spp.	+	*Gibbium psylloides*			4
Tribolium castaneum	+	*Tribolium* spp.			1
Tribolium confusum	+	*Attagenus* spp.	+	*Gibbium psylloides*	60
Tribolium confusum	+	*Attagenus* spp.	+	*Tribolium castaneum*	20
Tribolium castaneum	+	*Tribolium* spp.	+	*Gibbium psylloides*	20

* Percentages are based on the total number of occurrences for combinations of two ($n = 70$) and three ($n = 5$) arthropods; $n =$ number of arthropods.

Quebec

The most common association that included two kinds of insects in Quebec flour mills occurred between *Tribolium castaneum* and *Sitophilus oryzae*, and between *Tenebrio molitor* and *Attagenus* spp. (Table 31). The second most common association occurred between *Tribolium castaneum* and *S. granarius*, and between *Tenebrio molitor* and *S. granarius*. Six other associations of two kinds of insects also occurred with various combinations of the same species or species groups.

The most common association that included three kinds of insects occurred among *Attagenus* spp., *T. molitor*, and *S. granarius*. Also occurring were six other combinations with three kinds of insects having 11% frequency of association and three other combinations having 6% frequency of association (Table 31).

Maritime Provinces

The single most common association included two kinds of insects in maritime flour mills and occurred between *Tribolium* spp. and *T. destructor* (Table 32). The two other associations occurred between *Tribolium* spp. and *Cryptolestes* spp., and between *Tribolium castaneum* and *Alphitobius diaperinus*.

Grain elevator category

British Columbia

The two most common associations that included two kinds of insects in terminal elevators in British Columbia occurred between *Hofmannophila pseudospretella* and *Endrosis sarcitrella*, and between *H. pseudospretella* and *Tenebrio molitor* (Table 33). The three other associations occurring with 10–12% frequency were between *E. sarcitrella* and *T. molitor*, between *H. pseudospretella* and *Ptinus* spp., and between *Ptinus* spp. and *T. molitor*. Five other less common associations between two kinds of insects or insect groups are listed in Table 33.

The most common association that included three kinds of insect species occurred among *H. pseudospretella*, *E. sarcitrella*, and *T. molitor*, with 18% frequency of occurrence. Nine other associations of this type—i.e., including moths and beetle species in various combinations—occurred with 5–15% frequency (Table 33).

Thunder Bay, Ont.

The single most common association that included two kinds of stored-product arthropods occurred, with 33% frequency, between *Tenebrio molitor* and mites (Table 34). The second most common association, with 17% frequency, included *Cryptolestes ferrugineus* and mites. Some of the other less common associations included the following pairs of insect species: *T. molitor* and *Nemapogon granella*; *T. molitor* and *C. ferrugineus*; and *C. ferrugineus* and *N. granella*.

Table 31. Frequency of association of the most common stored-product arthropods in flour mills in Quebec (1969–1981)

Arthropods					Frequency of association (%*)
Tribolium castaneum	+	*Sitophilus oryzae*			14
Tenebrio molitor	+	*Attagenus* spp.			14
Tribolium castaneum	+	*Sitophilus granarius*			12
Tenebrio molitor	+	*Sitophilus granarius*			12
Tenebrio molitor	+	*Tribolium castaneum*			10
Attagenus spp.	+	*Sitophilus granarius*			10
Attagenus spp.	+	*Tribolium castaneum*			8
Tenebrio molitor	+	*Sitophilus oryzae*			8
Sitophilus granarius	+	*Sitophilus oryzae*			6
Attagenus spp.	+	*Sitophilus oryzae*			6
Attagenus spp.	+	*Tenebrio molitor*	+	*Sitophilus granarius*	17
Tribolium castaneum	+	*Sitophilus oryzae*	+	*Sitophilus granarius*	11
Tribolium castaneum	+	*Tenebrio molitor*	+	*Sitophilus granarius*	11
Tribolium castaneum	+	*Attagenus* spp.	+	*Sitophilus oryzae*	11
Tribolium castaneum	+	*Tenebrio molitor*	+	*Sitophilus oryzae*	11
Tribolium castaneum	+	*Tenebrio molitor*	+	*Attagenus* spp.	11
Attagenus spp.	+	*Tenebrio molitor*	+	*Sitophilus oryzae*	11
Tribolium castaneum	+	*Attagenus* spp.	+	*Sitophilus granarius*	6
Attagenus spp.	+	*Sitophilus oryzae*	+	*Sitophilus granarius*	6
Tenebrio molitor	+	*Sitophilus oryzae*	+	*Sitophilus granarius*	6

* Percentages are based on the total number of occurrences for combinations of two ($n = 50$) and three ($n = 18$) arthropods; $n =$ number of arthropods.

Table 32. **Frequency of association of the most common stored-product arthropods in flour mills in the Maritime Provinces (1969–1981)**

Arthropods			Frequency of association (%*)
Tribolium spp.	+	*Tribolium destructor*	67
Tribolium spp.	+	*Cryptolestes* spp.	17
Tribolium castaneum	+	*Alphitobius diaperinus*	17

* Percentages are based on the total number of occurrences for combinations of two ($n = 3$) arthropods; $n =$ number of arthropods.

Table 33. Frequency of association of the most common stored-product arthropods in grain elevators in British Columbia (1969–1981)

Arthropods					Frequency of association (%*)
Hofmannophila pseudospretrella	+	*Endrosis sarcitrella*			17
Hofmannophila pseudospretella	+	*Tenebrio molitor*			16
Endrosis sarcitrella	+	*Tenebrio molitor*			12
Hofmannophila pseudospretella	+	*Ptinus* spp.			10
Ptinus spp.	+	*Tenebrio molitor*			10
Hofmannophila pseudospretella	+	Lepidoptera spp.			9
Endrosis sarcitrella	+	Lepidoptera spp.			7
Endrosis sarcitrella	+	*Ptinus* spp.			7
Tenebrio molitor	+	Lepidoptera spp.			7
Ptinus spp.	+	Lepidoptera spp.			5
Hofmannophila pseudospretella	+	*Endrosis sarcitrella*	+	*Tenebrio molitor*	18
Hofmannophila pseudospretella	+	*Ptinus* spp.	+	*Tenebrio molitor*	15
Hofmannophila pseudospretella	+	*Endrosis sarcitrella*	+	Lepidoptera spp.	10
Hofmannophila pseudospretella	+	*Endrosis sarcitrella*	+	*Ptinus* spp.	10
Hofmannophila pseudospretella	+	Lepidoptera spp.	+	*Tenebrio molitor*	10
Ptinus spp.	+	*Endrosis sarcitrella*	+	*Tenebrio molitor*	10
Hofmannophila pseudospretella	+	Lepidoptera spp.	+	*Ptinus* spp.	8
Lepidoptera	+	*Endrosis sarcitrella*	+	*Tenebrio molitor*	8
Ptinus spp.	+	Lepidoptera spp.	+	*Tenebrio molitor*	8
Ptinus spp.	+	*Endrosis sarcitrella*	+	Lepidoptera spp.	5

* Percentages are based on the total number of occurrences for combinations of two ($n = 58$) and three ($n = 40$) arthropods; n = number of arthropods.

Table 34. Frequency of association of the most common stored-product arthropods in grain elevators in Thunder Bay, Ont. (1969–1981)

Arthropods					Frequency of association (%*)
Tenebrio molitor	+	Mites			33
Cryptolestes ferrugineus	+	Mites			17
Tenebrio molitor	+	*Nemapogon granella*			11
Tenebrio molitor	+	*Cryptolestes ferrugineus*			11
Lepidoptera	+	Mites			11
Lepidoptera	+	*Cryptolestes ferrugineus*			11
Cryptolestes ferrugineus	+	*Nemapogon granella*			6
Cryptolestes ferrugineus	+	Mites	+	Lepidoptera spp.	50
Cryptolestes ferrugineus	+	*Nemapogon granella*	+	*Tenebrio molitor*	25
Cryptolestes ferrugineus	+	Mites	+	*Tenebrio molitor*	25

* Percentages are based on the total number of occurrences for combinations of two ($n = 18$) and three ($n = 4$) arthropods; $n =$ number of arthropods.

The following three associations included three kinds of arthropods and occurred with 25–50% frequency: *C. ferrugineus*, mites, and Lepidoptera spp.; *C. ferrugineus*, *N. granella*, and *T. molitor*; and *C. ferrugineus*, mites, and *T. molitor* (Table 34).

Ontario

The single most common association that included two kinds of arthropods occurred, with 22% frequency, between *Nemapogon granella* and *Tenebrio molitor* (Table 35). Of the nine other less common associations of this type the following four pairs occurred with 11–13% frequency: *Attagenus* spp. and *T. molitor*; mites and *T. molitor*; *Cryptolestes ferrugineus* and *T. molitor*; and *C. ferrugineus* and *N. granella*.

The most common association that included three kinds of arthropods was among *N. granella*, *T. molitor*, and *C. ferrugineus* and occurred with 23% frequency (Table 35). Of the nine other less common associations of this type, the following combinations occurred with more than 10% frequency: *N. granella*, *T. molitor*, and *Attagenus* spp.; *N. granella*, *T. molitor*, and mites; and *C. ferrugineus*, *T. molitor*, and *Attagenus* spp. The six remaining three-kind arthropod combinations also included the above-mentioned kinds of arthropods. It seems that the habitat and climatic conditions provided by terminal elevators in southern Ontario are uniquely suitable for multiplication of several species of beetles and mites and one species of stored-product moth.

Quebec

The single most common association that included two kinds of arthropods occurred, with 19% frequency, between *Tenebrio molitor* and *Attagenus* spp. (Table 36). Of the nine other less common associations of this type, the following three pairs occurred with 10–16% frequency: *T. molitor* and *Nemapogon granella*; *T. molitor* and *Cryptolestes ferrugineus*; and *T. molitor* and *Sitophilus granarius*. The two most common associations that included three kinds of arthropods occurred among *T. molitor*, *Attagenus* spp., and *N. granella*, with 15% frequency of occurrence, and *T. molitor*, *Attagenus* spp., and *C. ferrugineus*, with 14% frequency.

Maritime Provinces

The single most common association that included two kinds of arthropods occurred, with 30% frequency, between *Nemapogon granella* and *Tenebrio molitor* (Table 37). Of the eight less common associations of this type, the two pairs that occurred with 11–26% frequency were *N. granella* and mites, and *N. granella* and *Hofmannophila pseudospretella*.

The most common association that included three kinds of arthropods occurred among *N. granella*, *T. molitor*, and mites, with 25% frequency. Of the six other less common associations of this type, the following three combinations occurred with 17% or higher frequency: *N. granella*, *H. pseudospretella*, and mites; *N. granella*, *T. molitor*, and *H. pseudospretella*; and *N. granella*, *Cryptolestes ferrugineus*, and mites.

Table 35. Frequency of association of the most common stored-product arthropods in grain elevators in Ontario (1969–1981)

Arthropods					Frequency of association (%*)
Nemapogon granella	+	*Tenebrio molitor*			22
Attagenus spp.	+	*Tenebrio molitor*			13
Mites	+	*Tenebrio molitor*			13
Cryptolestes ferrugineus	+	*Tenebrio molitor*			12
Cryptolestes ferrugineus	+	*Nemapogon granella*			11
Attagenus spp.	+	*Nemapogon granella*			9
Cryptolestes ferruginus	+	*Attagenus* spp.			6
Mites	+	*Cryptolestes ferrugineus*			6
Mites	+	*Nemapogon granella*			4
Mites	+	*Attagenus* spp.			4
Nemapogon granella	+	*Tenebrio molitor*	+	*Cryptolestes ferrugineus*	23
Nemapogon granella	+	*Tenebrio molitor*	+	*Attagenus* spp.	19
Nemapogon granella	+	*Tenebrio molitor*	+	Mites	10
Cryptolestes ferrugineus	+	*Tenebrio molitor*	+	*Attagenus* spp.	10
Nemapogon granella	+	*Cryptolestes ferrugineus*	+	*Attagenus* spp.	8
Cryptolestes ferrugineus	+	*Tenebrio molitor*	+	Mites	8
Nemapogon granella	+	Mites	+	*Attagenus* spp.	6
Mites	+	*Tenebrio molitor*	+	*Attagenus* spp.	6
Nemapogon granella	+	*Cryptolestes ferrugineus*	+	Mites	4
Mites	+	*Cryptolestes ferrugineus*	+	*Attagenus* spp.	4

* Percentages are based on the total number of occurrences for combinations of two ($n = 123$) and three ($n = 48$) arthropods; $n =$ number of arthropods.

Table 36. Frequency of association of the most common stored-product arthropods in grain elevators in Quebec (1969–1981)

Arthropods					Frequency of association (%*)
Tenebrio molitor	+	*Attagenus* spp.			19
Tenebrio molitor	+	*Nemapogon granella*			16
Tenebrio molitor	+	*Cryptolestes ferrugineus*			11
Tenebrio molitor	+	*Sitophilus granarius*			10
Attagenus spp.	+	*Nemapogon granella*			8
Cryptolestes ferrugineus	+	*Nemapogon granella*			8
Attagenus spp.	+	*Cryptolestes ferrugineus*			8
Attagenus spp.	+	*Sitophilus granarius*			7
Sitophilus granarius	+	*Nemapogon granella*			6
Sitophilus granarius	+	*Cryptolestes ferrugineus*			6
Tenebrio molitor	+	*Attagenus* spp.	+	*Nemapogon granella*	15
Tenebrio molitor	+	*Attagenus* spp.	+	*Cryptolestes ferrugineus*	14
Tenebrio molitor	+	*Attagenus* spp.	+	*Sitophilus granarius*	12
Tenebrio molitor	+	*Cryptolestes ferrugineus*	+	*Nemapogon granella*	12
Tenebrio molitor	+	*Sitophilus granarius*	+	*Nemapogon granella*	9
Tenebrio molitor	+	*Cryptolestes ferrugineus*	+	*Sitophilus granarius*	9
Cryptolestes ferrugineus	+	*Attagenus* spp.	+	*Nemapogon granella*	9
Sitophilus granarius	+	*Attagenus* spp.	+	*Nemapogon granella*	7
Cryptolestes ferrugineus	+	*Sitophilus granarius*	+	*Nemapogon granella*	7
Cryptolestes ferrugineus	+	*Attagenus* spp.	+	*Sitophilus granarius*	6

* Percentages are based on the total number of occurrences for combinations of two ($n = 261$) and three ($n = 124$) arthropods; $n =$ number of arthropods.

Table 37. Frequency of association of the most common stored-product arthropods in grain elevators in the Maritime Provinces (1969–1981)

Arthropods					Frequency of association (%*)
Nemapogon granella	+	*Tenebrio molitor*			30
Nemapogon granella	+	Mites			26
Nemapogon granella	+	*Hofmannophila pseudospretella*			11
Mites	+	*Tenebrio molitor*			8
Mites	+	*Hofmannophila pseudospretella*			7
Mites	+	*Cryptolestes ferrugineus*			6
Nemapogon granella	+	*Cryptolestes ferrugineus*			5
Hofmannophila pseudospretella	+	*Tenebrio molitor*			5
Cryptolestes ferrugineus	+	*Tenebrio molitor*			2
Nemapogon granella	+	*Tenebrio molitor*	+	Mites	25
Nemapogon granella	+	*Hofmannophila pseudospretella*	+	Mites	21
Nemapogon granella	+	*Tenebrio molitor*	+	*Hofmannophila pseudospretella*	17
Nemapogon granella	+	*Cryptolestes ferrugineus*	+	Mites	17
Nemapogon granella	+	*Tenebrio molitor*	+	*Cryptolestes ferrugineus*	8
Cryptolestes ferrugineus	+	*Tenebrio molitor*	+	Mites	8
Hofmannophila pseudospretella	+	*Tenebrio molitor*	+	Mites	8

* Percentages are based on the total number of occurrences for combinations of two ($n = 84$) and three ($n = 24$) arthropods; $n =$ number of arthropods.

Feed mill category

Prairie Provinces

The frequency of association of the most common kinds of arthropods in feed mills during 1969–1981 recorded from the Prairie Provinces is listed in Table 38. The two most common associations that included two kinds of arthropods occurred between *Tribolium confusum* and *Trogoderma inclusum* (28% frequency), and between *Tribolium confusum* and *Attagenus* spp. (22% frequency). The third most common association occurred between *T. confusum* and *T. castaneum* (13% frequency). Of the five other less common associations, the following pairs are noteworthy: *Trogoderma inclusum* and *Attagenus* spp.; *T. inclusum* and *Tribolium castaneum*; and *T. castaneum* and *Attagenus* spp.

Common associations that included three kinds of insects and occurred with 23% frequency were *Tribolium confusum*, *Trogoderma inclusum*, and *Attagenus* spp.; *Tribolium confusum*, *Trogoderma inclusum*, and *Tribolium castaneum*; *T. confusum*, *Attagenus* spp., and *T. castaneum*; and *Trogoderma inclusum*, *Attagenus* spp., and *Tribolium castaneum* (Table 38). General conditions and microenvironments provided by feed mills in the temperate continental climate of the Prairie Provinces probably favor the development and multiplication of stored-product species that belong to the genera *Tribolium*, *Trogoderma*, and *Attagenus*.

Table 38. Frequency of association of the most common stored-product arthropods in feed mills in the Prairie Provinces (1969–1981)

Arthropods					Frequency of association (%*)
Tribolium confusum	+	*Trogoderma inclusum*			28
Tribolium confusum	+	*Attagenus* spp.			22
Tribolium confusum	+	*Tribolium castaneum*			13
Trogoderma inclusum	+	*Attagenus* spp.			9
Trogoderma inclusum	+	*Tribolium castaneum*			9
Tribolium castaneum	+	*Attagenus* spp.			9
Tribolium confusum	+	*Tribolium* spp.			6
Trogoderma inclusum	+	*Tribolium* spp.			3
Tribolium confusum	+	*Trogoderma inclusum*	+	*Attagenus* spp.	23
Tribolium confusum	+	*Trogoderma inclusum*	+	*Tribolium castaneum*	23
Tribolium confusum	+	*Attagenus* spp.	+	*Tribolium castaneum*	23
Trogoderma inclusum	+	*Attagenus* spp.	+	*Tribolium castaneum*	23
Trogoderma inclusum	+	*Tribolium* spp.	+	*Tribolium confusum*	8

* Percentages are based on the total number of occurrences for combinations of two ($n = 32$) and three ($n = 13$) arthropods; $n =$ number of arthropods.

CHAPTER 10 ANALYSIS OF PESTICIDE USE

The extent of pesticide use in terminal grain elevators, flour mills, feed mills, and other cereal-processing plants provides a good indication of infestation problems throughout the grain-handling system. The technical staff in these storage and grain-processing facilities were contacted, therefore, to determine the materials used for pest control and the effectiveness of recommended control methods. The results of this survey were tabulated to determine the main problems associated with pest control activities carried out to conform with standards necessary for the issuance of phytosanitary certificates by the Pesticide Division of the Food Production and Inspection Branch of Agriculture Canada. The certificates are required by certain countries to ensure that the products they import are manufactured or processed in premises that are essentially free from pest infestations. The incidence of pesticide use was more frequent during 1975–1980 than during 1969–1974 (Table 39), reflecting a greater emphasis on pest control in the cereal industries.

Terminal grain elevators

Terminal grain elevators are inspected less frequently than flour mills. The main locations requiring treatment are storage silos, which are usually fumigated with phosphine (Tables 39–41). The treatments are carried out by trained staff or by pest control operators who also deal with vertebrate pest control problems. Malathion and synergized pyrethrins are applied as sprays or fogs to control beetles and moths on structural surfaces or in working areas throughout the elevator. Two out of seven respondents reported unsatisfactory control with insecticides, perhaps because control measures were applied less frequently in elevators than in flour mills, resulting in ineffective application. All elevators had problems with mice, rats, or birds.

Flour mills

Most flour mills are inspected daily or weekly by staff that are trained in pest control. All areas of the mill, milling machinery, spouts, and conveyors require treatment with pest control chemicals, usually once a month. The spot fumigant Dawson 73 (70% ethylene dibromide plus 30% methyl bromide, by volume) is the fumigant most often applied to control insects in milling machinery and spouts where cereal stocks accumulate and provide favorable conditions for insects to feed and multiply (Tables 39–41). The fumigant EB15 (15% ethylene dibromide plus 85% carbon tetrachloride, by volume) is also used.

Insects and moths also infest the outside surfaces of milling machinery, floor areas, and the interior structures of flour mills. The insecticides malathion and synergized pyrethrins are applied as sprays or fogs to control infestations. The technical staff of flour mills reported that all insecticides and fumigants provided good control of insect pests when applied on a monthly basis. Only one mill in the Prairie Provinces reported the use of an annual freeze-out to control insects in a flour mill.

Table 39. **Number of reports (n) of pesticide use in grain elevators ($n = 7$), flour mills ($n = 17$), and feed mills ($n = 8$) in Canada (1969–1980)**

Pesticide	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	Total
Grain elevators													
Malathion	1	1	1	0	1	1	6	6	9	16	35	29	106
Phosphine	0	0	2	0	3	3	5	6	0	4	4	10	37
Unspecified*	4	11	8	5	40	45	39	43	43	26	37	32	333
Flour mills													
Malathion	0	0	0	0	1	0	0	2	2	5	18	8	36
Phosphine	0	0	0	0	0	0	0	0	1	0	1	2	4
Unspecified*	—	4	6	8	35	47	49	49	48	66	72	76	460
Feed mills													
Malathion	0	0	0	0	0	0	0	0	0	4	5	4	13
Phosphine	0	0	0	0	0	0	0	0	1	0	1	1	3
Unspecified*	—	—	—	—	—	13	12	13	10	23	22	40	133

* Unspecified pesticides include spot fumigants such as EDB–MB and EB15, insecticide sprays, or fogs that contain pyrethrins or dichlorovos, applied at recommended rates stated on the manufacturer's label.

Table 40. Number of times pesticides were used in grain elevators, flour mills, and feed mills in Canada (1969–1980), according to severity of infestation

Pesticide	Severity of infestation (no. of insects found per inspection) 1–2	3–5	6–10	10+	Total
	Grain elevators				
Malathion	87	61	18	60	226
Phosphine	79	26	17	20	142
Unspecified*	232	131	74	146	583
	Flour mills				
Malathion	45	21	7	8	81
Phosphine	6	7	3	6	22
Unspecified*	245	185	76	117	623
	Feed mills				
Malathion	25	15	2	16	58
Phosphine	5	3	3	9	20
Unspecified*	62	46	34	37	179

* Unspecified pesticides include spot fumigants such as EDB–MB and EB15, insecticide sprays, or fogs that contain pyrethrins or dichlorovos, applied at recommended rates stated on the manufacturer's label.

Table 41. Pesticides used to control the top 10 kinds of arthropods in grain elevators, flour mills, and feed mills in Canada (1969–1980)

Arthropod	Pesticide		
	Malathion (%)	Phosphine (%)	Unspecified* (%)
	Grain elevators		
Tenebrio molitor	18.4	13.4	18.4
Nemapogon granella	11.8	12.7	11.7
Attagenus spp.	5.3	6.3	13.4
Cryptolestes ferrugineus	5.3	16.2	5.7
Mites	6.1	3.5	3.8
Sitophilus granarius	4.4	7.7	4.8
Cryptolestes spp.	2.6	8.5	2.9
Sitophilus oryzae	2.2	3.5	3.4
Pyralis farinalis	5.3	2.1	2.6
Tenebroides mauritanicus	3.1	2.1	3.3
	Flour mills		
Tribolium castaneum	11.1	4.5	37.5
Tribolium confusum	12.3	9.1	10.3
Tribolium spp.	3.7	0	3.7
Attagenus unicolor	6.2	13.6	4.5
Sitophilus granarius	8.6	4.5	5.5
Gibbium psylloides	4.9	4.5	2.1
Tenebrio molitor	6.2	4.5	3.6
Cryptolestes ferrugineus	11.1	13.6	3.1
Cryptolestes spp.	0	0	3.4
Tenebroides mauritanicus	2.5	4.5	2.9

		Feed mills	
Tribolium castaneum	6.9	10.0	15.1
Tribolium confusum	15.5	10.0	12.8
Attagenus spp.	12.1	10.0	10.1
Nemapogon granella	10.3	15.0	6.1
Cryptolestes ferrugineus	8.6	15.0	6.1
Tenebrio molitor	6.9	5.0	5.0
Oryzaephilus surinamensis	0	0	5.0
Plodia interpunctella	5.2	5.0	3.4
Tribolium spp.	1.7	0	1.7
Tenebroides mauritanicus	3.4	5.0	3.4

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* Unspecified pesticides include spot fumigants such as EDB-MB and EB15, insecticide sprays, or fogs that contain pyrethrins or dichlorovos, applied at recommended rates stated on the manufacturer's label.

Feed mills and other cereal-processing plants

This category of facilities, which includes feed mills, oat mills, and malting plants, is inspected daily or weekly by operational staff (Tables 39–41). Most respondents reported that all areas of the plant required treatment with fumigants or insecticides every month. A fogging machine was used to apply malathion or synergized pyrethrins in five of eight plants. One plant reported unsatisfactory control with insecticides applied by plant personnel. Some plants used untrained staff to apply pest control chemicals. The main areas that required treatment to control insects were grain storage bins and bins containing the finished products.

Analysis of reports

An analysis of inspection reports, pesticide usage, pests identified, and their frequency of occurrence in relation to the type of storage facility and the insecticide used has been summarized in Tables 39–41. Tables 39 and 40 indicate the pattern of pesticide use in the three different classes of storage. The unspecified pesticides include spot fumigants (EDB-MB, EB15), insecticide sprays, and fogs. These are the treatments most frequently used in the three types of facilities. Table 41 shows the incidence of the 10 most common insect species in each facility and the type of insecticide used to control them.

CHAPTER 11 DESCRIPTION, BIOLOGY, AND ECOLOGY OF SELECTED STORED-PRODUCT INSECT SPECIES

Only those stored-product insects that occur most frequently (in each storage category) in the course of regular inspection of cereals, oilseeds, and their products destined for export are given in detail below. Descriptions of two other insect species, *Trogoderma granarium* and *Tribolium madens*, are also included because of their special quarantine status in Canada.

Order: Coleoptera
Family: Cucujidae

Ahasverus advena (Waltl)

Synonym: *Cathartus advena* Waltl
Common name: foreign grain beetle

Economic importance. *Ahasverus advena* is a secondary pest of stored grain. It is both fungivorous and granivorous, usually infesting damp and decaying mold-damaged cereals, oilseeds, and other stored food. The presence of this insect in farm-stored grain is taken as a warning that the grain is beginning to spoil and become moldy. *A. advena* causes loss of quality in stored products by contamination with various life stages, body parts, cast skins, and feces and causes direct and indirect damage to many foodstuffs stored with a high moisture content. In Canada's Prairie Provinces and in parts of continental northern United States, it is frequently associated with hot spots in farm-stored grain.

Geographical distribution. *Ahasverus advena* is cosmopolitan and may have originated in temperate North America and spread to subtropical and tropical parts of the world. *A. advena* is common on farms in all provinces of Canada, and in northern and midwestern United States.

Climatic adaptability. *Ahasverus advena* can overwinter in damp and moldy grain in the continental temperate climate of Western Canada, Minnesota, North Dakota, and other parts of North America . This species also occurs in the humid tropical parts of Africa and India.

Food. Although primarily a fungivorous species, *Ahasverus advena* also infests and presumably feeds on various other foods, particularly when they are damp and moldy. It is usually reported in the following produce: corn, wheat, barley, oats, other cereals and their products, copra, cocoa, palm kernels, coffee, peanuts, spices, herbs, roots, beans, apple pomace, dead animals (dried), milo, mixed feeds, orange pomace, safflower seed, and stale cake. *A. advena* feeds and develops well on pure cultures of several seed-borne fungi, including *Aspergillus* *amstelodami* (Mangin) Thom and Church, *A. repens* (de Bary), *A. conicus* Blochwitz, *A. candidus* Link, *A. chevalieri* (Mangin) Thom and Church, *Penicillium citrinum* Thom, *Cladosporium* sp., and *Alternaria* sp. The presence of living fungi does not appear to be an essential component in the diet of this insect, but such fungi may supplement an otherwise inadequate diet. The following diets, even when they are not contaminated with fungi, can provide a complete diet for feeding and multiplication of *A. advena*: wheat germ, rolled oats plus yeast, rolled oats plus wheat germ, whole-wheat flour plus wheat germ, and whole-wheat flour plus yeast. Both yeasts and fungi may play an important role in causing enzyme breakdown of starchy foods into nutrients required by this insect species.

Type of damage and symptoms. Large populations of *Ahasverus advena* are found in moist, moldy, and decaying material. Thus, the presence of this species can be considered a bioindicator of insect contamination, of incipient major loss of quality of the food substrate by fungal damage, and of a rise in fat acidity.

Description. The adult beetle is robust, brown, and 2–3 mm long. Its antenna is slender; the three outer segments are longer than the rest; the length of the antenna is less than the length of the body. The prothorax is equipped with a single large tooth (rounded, tubelike) on each apical angle; the disk is evenly convex. Adults can fly. Eggs are glossy, white, elongated, and cylindrical, approximately 0.53 mm long and 0.21 mm wide. Freshly hatched larvae are white; the late-instar larvae are grayish white, with the last few abdominal segments darker and very active. The larvae lack a pair of horns (cerci) at the end of the body. The body length and the width of the head capsule (in parenthesis) of each larval instar (I–V) are as follows: I, 0.81 mm (0.19 mm); II, 1.55 mm (0.26 mm); III, 2.98 mm (0.33 mm); IV, 4.0 mm (0.43 mm); and V, 4.37 mm (0.45 mm). Before pupation, the larva isolates itself by forming a chamber of food particles cemented together, and then secretes from its anal aperture a brownish fluid that attaches the larva (now called a prepupa) to the substrate. The pupa is translucent white with darkish brown eyes and is about 2.2 mm long when mature.

Similarities to other insects. *Ahasverus advena* is superficially similar to the squarenecked grain beetle, *Cathartus quadricollis*, and the sawtoothed grain beetle, *Oryzaephilus surinamensis*; but *A. advena* is shorter and stouter than both and lacks six sawtoothed-like projections on the side of its prothorax, like those of *O. surinamensis*. *A. advena* can be separated from *Cryptolestes ferrugineus*, with which it is frequently associated, by its larger size, less flattened body, and the presence of a single blunt tooth on each apical corner of the prothorax.

Physical limits and optimum rate of multiplication. Complete development of *Ahasverus advena* occurs at 25–30°C and 60–100% relative humidity. Temperature limits for complete development and the intrinsic rate of natural increase are unknown. The optimum condition for egg to adult development is 27–30°C and 85–92% relative humidity.

Life cycle. Female beetles lay eggs singly (occasionally in clusters of two or three). At 27°C and 75% relative humidity an average of 1.46 eggs per day can be produced by a single female; 100–300 eggs per female can be laid in 135 days. Eggs hatch in 4 days, and the larval period ranges from 11 to 19 days. There are four to five larval instars, with average duration (in days) of each larval instar as follows: I, 3.6; II, 2.4; III, 2.4; IV, 2.2; and V, 2.2. A prepupal period lasting for 1–2 days precedes the 3–5 day pupal period. The life cycle from egg laying to adult emergence ranges from 19 to 24 days at 27°C and 66–92% relative humidity when insects are reared on rolled oats and brewer's yeast (95:5 by weight). When reared on fungi at 27°C and 85% relative humidity, *Ahasverus advena* can complete its life cycle in 17–20 days on *Aspergillus amstelodami*, 22–34 days on *A. candidus*, 16–23 days on *Penicillium citrinum*, and 19–24 days on *Cladosporium* sp.

Ecology. In a naturally occurring hot spot in bulk-stored oats in Manitoba, *Ahasverus advena* occurred in winter and spring in moldy wheat and oats already infested by *Oryzaephilus surinamensis* and *Cryptolestes ferrugineus*. The presence of *A. advena* here was part of an ecological succession of insects, mites, and microflora. All stages of the insect occurred when the grain temperature ranged from 7 to 42°C, usually at 18–36°C, and moisture content ranged from 15 to 27%. The associated microflora were *Penicillium* and *Streptomyces*, *Aspergillus*, *Rhizopus*, and *Absidia*. In Britain, *A. advena* survives in heated buildings and in such places as haystacks, which are kept warm by slow fermentation. In Minnesota and other major grain-storage areas of the United States, *A. advena* occurs in tough and moldy corn bulks stored in large metal bins on farms. Such deteriorating grain is usually about 1 year old and infested with *Sitophilus oryzae*, *S. zeamais*, *Plodia interpunctella*, *Cryptolestes pusillus*, *C. ferrugineus*, and mites. Being a strong flier, *A. advena* moves freely from granary to granary and from food store to food store on warm days, in countries with both temperate and tropical climates.

Natural enemies. Heavy infestation of moldy grain is often associated with two species of parasitic bethylid wasp, *Cephalonomia waterstoni* Gahan and *C. tarsalis* (Ashmead), and an insect predator *Xylocoris galactinus* (Fieb.). These parasites and predators attack the larvae of *Ahasverus advena*.

Order: Coleoptera
Family: Cucujidae

Cryptolestes ferrugineus **(Stephens)**

Synonyms: *Laemophloeus ferrugineus* Stephens, *Laemophloeus testaceus* Fabricius
Common names: rusty grain beetle (rust-red grain beetle)

Economic importance. *Cryptolestes ferrugineus* is a cosmopolitan insect pest of unprocessed cereals and oilseeds and occasionally of their products. It is the most common and serious pest of stored grain on farms and elevators in the Prairie

Provinces of Canada, where it can cause widespread grain infestation and outbreaks under certain conditions. When freshly harvested grain is stored at a high temperature at harvest for periods ranging from several months to years, *C. ferrugineus* can build up large populations and may become a major cause of grain heating and spoilage. Insect-infested heated grain is likely to cake, to become moldy and musty, to change in free fatty acid levels, to sprout, and to undergo loss in germination and in milling and baking quality. Insect-infested grain must be fumigated before buyers will accept it. Infestations, however, are frequently not detected, resulting in contaminated storage and transportation facilities. Because this species cannot penetrate an undamaged cereal seed, it is considered a secondary pest of relatively dry stored grain in many countries of the world.

Geographical distribution. *Cryptolestes ferrugineus* is widely distributed both in the temperate and tropical parts of the world. In tropical and subtropical regions of Africa, *C. ferrugineus* is a pest of oilseeds, cocoa beans, and cowpeas. In North America this species is most common in the southern parts of Canada and northern United States. Some of the other countries from which it has been reported are United Kingdom, Argentina, Brazil, Kenya, South Africa, Togo, Nigeria, India, Burma, Australia, and USSR.

Climatic adaptability. *Cryptolestes ferrugineus* is both cold-hardy and tolerant of low relative humidity. In unheated granaries it can survive extremely low winter temperatures in Canada, northern parts of the United States, and Britain. Although the air temperature above the bulk grain in such granaries ranges from –10 to –40°C, in some winters the temperature in the intergranular spaces within the bulk or bagged grain where the insects survive ranges from –5 to –10°C. Its unusual ability to acclimate to low temperature enables *C. ferrugineus* to survive the severe winters of Canada and the USSR. *C. ferrugineus* has a climatic plasticity index of 570, which is among the highest of the 51 stored-product insects considered. Only *Tribolium castaneum* and *Ephestia kuehniella* have higher plasticity indexes than *C. ferrugineus*. *C. ferrugineus* is more common in the middle latitude lands of the world, particularly in those countries that have a continental climate with a short summer and that grow and store spring wheat, barley, and oats. It has been predicted, often with verification from infestation records, that *C. ferrugineus* when put into storage in warm harvested grain at 27–35°C can thrive in unheated granaries only in those areas where a mean monthly grain temperature of more than 20°C is maintained for at least 3 months of the year.

Food. *Cryptolestes ferrugineus* feeds almost exclusively on the germ, as it cannot penetrate completely sound seed. Although superficially sound, most grain masses contain some seed with broken seed coats, which are prone to infestation by this insect. Whole seeds of rye, wheat, and millet (usually with some seed coat injury) are a more favorable food than most other crops. Its other foods include pulse, cocoa, rice, rice bran, cereal products, pulse products, corn, barley, sunflower, flax, soybeans, and millet. This insect does not usually multiply on whole or crushed seed of mustard, rapeseed, or clover. *C. ferrugineus* feeds and can multiply exclusively on some species of the following seed-borne fungal genera: *Alternaria*, *Curvularia*, *Fusarium*, *Mucor*, *Nigrospora*, *Penicillium*, *Stemphylium*, and *Trichothecium*.

Type of damage and symptoms. Typical damage caused by *Cryptolestes ferrugineus* to a grain kernel can be recognized by the presence of a distinct burrowing hole in the germ area made by the emerging adult (Fig. 24). Examination of the dissected seed germ under a stereomicroscope shows the insect in one of its life stages, because the entire larval and pupal periods are usually passed inside burrows in the germ. *C. ferrugineus* is an efficient feeder on wheat germ; by the time a larva has reached the pupal stage it has consumed practically all of the germ. Six calories are contained in a wheat germ, which is about 4.8% of the energy contained in an average kernel of 126 calories. In bulk grain, heavy infestation of *C. ferrugineus* is associated with the development of localized hot spots, caking, mold growth, and sprouting at the top surface above the hot spot. This species is found in large numbers until the grain temperature rises to about 42°C, after which high mortality occurs. It has been suggested that through its own metabolic processes, this species can generate enough heat and moisture to create hot spots in bulk grain in cold weather, provided that the initial grain temperature and moisture content (14% or more) are favorable for its development. In farm granaries the insect-infested bulk grain (*C. ferrugineus* and *Tribolium castaneum*, for example) that includes a hot spot usually has a funnel-shaped appearance, narrow near the floor and expanding abruptly near the top surface, where a layer of sprouting damp grain is frequently found.

Description (Fig. 25). The adult is an extremely flat, rectangular, reddish brown beetle, 1.5–2.5 mm long, with V-shaped threadlike antennae (feelers). Its distinguishing characters are a thorax with lateral ridges, strongly to moderately contracted posteriorly; antenna about one-half the body-length, its terminal segment not more than twice as long as broad; head and thorax finely and usually sparsely punctured; only the male has a blunt external mandibular tooth on the underside of each mandible near the base. The egg is white and nearly translucent, elongate, about 0.76 mm long (range, 0.68–0.81 mm) and about 0.23 mm (range, 0.20–0.30 mm) wide. The larva is long (about 3 mm when fully grown), slender, white to straw-colored, with a flat body, the posterior half of which is slightly wider than the anterior half. The posterior end of the body contains two dark, slender horns (urogomphi). The pupa is about 2 mm long, translucent, white in the beginning and darker before the emergence of the adult. The pupa is often encased in a weak silken cocoon.

Similarities to other insects. In North America, adult *Cryptolestes ferrugineus* can be confused with two other *Cryptolestes* species, *C. pusillus* and *C. turcicus*. The combination of characters that follows is useful in separating the three species.

In *C. turcicus*, male antennae are longer than those of the female, nearly as long as the length of the body. Males lack a tooth at the base of the mandible. The pronotum is quadrate, or slightly narrowing posteriorly, with rear angles conspicuous. The frontoclypeal suture bulges towards the mouth parts. In males, the apodeme of the ninth segment does not extend to the first abdominal segment. In females, the bursa copulatrix is sinuate.

In *C. pusillus*, male antennal and mandibular characters are the same as those of *C. turcicus*. The pronotum is not quadrate except in small specimens, 1.5 times as wide as long. The frontoclypeal suture bulges away from the mouth parts. Elytra are shorter in proportion to the rest of the body. In males, accessory sclerite of the genitalia occurs as one crescent, with the posterior lobes of the penis not sclerotized. In females, the bursa copulatrix is spiral.

In *C. ferrugineus*, male and female antennae are of similar length, about one-half the body length. Males have a tooth at the base of the mandible. The pronotum is with distinct hind angles, its rear end slightly narrower than the front end. The frontoclypeal suture bulges towards the mouth parts. The head and pronotum are with sparse and fine punctures. In males, accessory sclerite of the genitalia occurs as two crescents with posterior lobes of the penis strongly sclerotized and associated with the accessory sclerites. In females, the bursa copulatrix is semicircular in outline.

Physical limits and optimum rate of multiplication. The physical limits of successful development and multiplication of *Cryptolestes ferrugineus* are 20–40°C and 40–95% relative humidity. The optimum for development and multiplication are 32–35°C and 70–90% relative humidity. The maximum rate of increase under favorable conditions is 60 times per lunar month. Well-acclimated *C. ferrugineus* can survive exposure to low temperature (–12°C) and low relative humidity (10%).

Life cycle. About 1–2 days after mating, a female begins to lay eggs. Eggs are deposited on or in the crevices of the grain kernels, in intergranular spaces, or in grain dust; up to 423 eggs can be laid by a female at 35°C and 70% relative humidity, although fewer are usually laid. The average number of eggs laid per day per female is about six. The average duration of life stages and the ranges, in days, at 32°C and 60–90% relative humidity are: egg, 3.8 (3.6–3.9); first instar, 4.1 (3.3–5.1); second instar, 3.0 (2.4–3.6); third instar, 3.5 (2.7–4.0); fourth instar, 6.8 (6.4–7.5); pupa, 4.3 (4.0–4.5); and egg-to-adult emergence, 25.37 (23.0–27.5). The egg-to-adult development period, at 75% relative humidity, ranges from 21 days at 38°C, 20 days at 32°C, 27 days at 27°C, and 94 days at 21°C. Its egg viability is 85% or higher from 22 to 38°C but only about 50% at 40°C and 70% relative humidity. The longevity of the adults of both sexes increases with decreasing temperature. Thus, a male lives an average 180 days at 21°C and 93 days at 32°C, whereas a female lives for 214 days at 21°C and 134 days at 32°C. Although primarily granivorous, preferring to feed and reproduce on wheat and rye kernels, *Cryptolestes ferrugineus* can complete development on at least 10 species of seed-borne fungi. At 33°C and 75% relative humidity, the egg-to-adult development time is 22 days on *Tricothecium roseum* Link and 34 days on *Fusarium moniliforme* Sheld., as compared with 23 days on wheat feed controls.

Ecology. In a grain mass, the distribution of *Cryptolestes ferrugineus* is controlled by its feeding and oviposition behavior—the insects gather in pockets of soft and damaged grain. Its dispersion is secondarily regulated by response to temperature; for example, 2% of adults are active at 15°C and 75% at 25°C. This insect's response to humidity is a minor factor in its dispersion. In wheat, *C. ferrugineus* moves preferentially to portions infected with certain fungi, e.g., *Penicillium corymbiferum* Corda. Repeated abrupt physical disturbance, such as dropping of wheat kernels freely or dropping bags from a 14-m height, can cause high mortality (up to 43%) in this species.

C. ferrugineus moves rapidly on warm days and can fly when the air temperature is above 23°C. Thus, during periods of bumper harvests in Western Canada, when open piles of grain are left on the ground, these sites become highly favorable locations for infestation by *C. ferrugineus*.

Heat (up to 42°C) generated by insects begins when the adult insects congregate and breed rapidly in dry pockets in the grain bulk. The heat produced by the respiration of the growing larvae also favors larval growth and promotes adult breeding. The grain temperature gradually rises, moisture from the insects dampens the grain, crusts form, and molds (molds also contribute to moisture production and heating) grow quickly. In extreme cases, the grain sprouts at the top of the bulk. As the top of the grain bulk is exposed to sub-zero temperatures in winter, convection currents of moist air inside the bulk cause moisture accumulation along the surface. Heating lasts for several months, and much damage from insects and molds occurs during the latter part of the heating period. Subsequently, other species of insects (*Ahasverus*, for example), mites (*Acarus*, for example), and bacteria invade the heated bulk grain. By the time the farmer sees the first signs of infestation, that is, heating, caking, and sprouting on the surface of the grain bulk, the damage has been done. In spring, insects spread from overcrowded quarters and contaminate the surrounding grain mass. Insect and mite infestations are usually restricted to a 30-cm layer of grain along the surface, but molds may grow the entire depth of the bulk grain from floor to the top surface.

Development of a hot spot in bulk grain is a complex process involving several variables. Principal-component analysis of physical, chemical, and biological variables in a 46-t oat bulk predominantly infested by *C. ferrugineus* and *Oryzaephilus surinamensis* in a farm granary in Manitoba, during the initiation and development of a hot spot, revealed successive interactions among several distinct groups of insects, fungi, and mites. The first (key) group included two insects, *Oryzaephilus* and *Cryptolestes*, and the postharvest fungus *Penicillium*; the second group included the preharvest fungi *Alternaria* and *Acremoniella*; and the third group included fungivorous insects (*Ahasverus*), mites (*Acarus*, *Lepidoglyphus*), and other predaceous and scavenger arthropod species. Moisture content of the seed greater than 15% and heat produced by the metabolic processes of arthropods contributed to the development of a successful winter hot spot.

Natural enemies. Two parasitic wasps (Hymenoptera, Bethylidae) that are the most important parasites of larval *Cryptolestes ferrugineus* are *Cephalonomia waterstoni* Gahan and *C. tarsalis* (Ashmead).

Order: Coleoptera
Family: Cucujidae

Cryptolestes pusillus (Schönherr)

Synonyms: *Laemophloeus pusillus* (Schönherr), *L. minutus* (Olivier), *Cryptolestes minutus* (Olivier), *Cucujus pusillus* Schönherr, *Cucujus testaceus* Stephens
Common name: flat grain beetle

Economic importance. *Cryptolestes pusillus* is one of the smallest and most common stored-product insects occurring frequently in cereals such as corn, wheat, and their products, in the tropics, in the northern half of the United States, particularly North Dakota and Minnesota, and in the eastern part of Canada. It is commonly imported into Europe. In 1977 and 1978, *Cryptolestes*, which included both *C. pusillus* and *C. ferrugineus*, was the second most common genus of insect pests found in export samples of wheat and corn taken from 79 port terminals in the United States and Canada (St. Lawrence Seaway). In Canada, *C. pusillus* is more common in southern Ontario than in the western provinces. Some of the past records of this species from the Prairie Provinces could have been those of *C. ferrugineus* or *C. turcicus*; *C. pusillus* is frequently confused with *C. turcicus*. *C. pusillus* cannot attack sound, completely dry grain, but thrives as a secondary insect pest, often as a scavenger in moist mold-damaged grain following an invasion by a primary granivorous insect, such as *Sitophilus oryzae*. Although it has been reported in the past, *C. pusillus*, unlike *C. turcicus*, is relatively rare in the machinery of flour mills.

Geographical distribution. *Cryptolestes pusillus* is cosmopolitan. Because it closely resembles two other *Cryptolestes* species, *C. ferrugineus* and *C. turcicus*, its distributional records have often been kept as a generic group or through the record of a single species. Past published distribution data, therefore, may not reflect the true distribution of *C. pusillus*. It now appears that *C. pusillus* is more common in the northern part of the United States than is *C. ferrugineus*, which predominates in Canada. Some of the countries outside North America where *C. pusillus* has been reported as a pest include India, Nigeria, Uganda, Britain, Portugal, Finland, Japan, Australia, Mexico, Argentina, Burma, Philippines, People's Republic of China, and Hong Kong.

Climatic adaptability. *Cryptolestes pusillus*, unlike its cold-hardy relative *C. ferrugineus*, is a relatively cold-susceptible species that needs high humidity to develop. *C. pusillus* is abundant in the wet tropical and warm temperate parts of the world, where it multiplies rapidly. In these areas it mainly infests beans, cassava, ground nuts, and corn; whereas in cooler, drier regions it infests mainly cereals and cereal products. It is relatively rare in the dry tropics. In the cool temperate climate of Britain, Ireland, and Western Canada, *C. pusillus* rarely survives the winter in unheated granaries. Some life stages (adults and pupae) of this species can survive from 2 to −0.5°C for 2.5–4 days.

Food. *Cryptolestes pusillus* feeds on damaged cereals and cereal products, preferring the embryo of cereal kernels. Wheat is probably the most favored diet, although it is known to infest corn, barley, palm kernels, dried bananas, benne seeds, bulbs, citrus pulp, filberts, sago, peaches, seaweed, rice, sorghum, brown rice, black-eyed peas, sunflower cake, peanuts, cotton seed, coffeeberries, cassava, copra, nutmeg, flour, cocoa beans, and seed-borne fungi. Characteristically, *C. pusillus* feeds on the germ of grain that has been damaged mechanically during harvest or by insects during storage.

Type of damage and symptoms. Damage caused by *Cryptolestes pusillus* is often of a secondary nature because it cannot physically penetrate undamaged grain. Nevertheless, the species is sometimes considered a primary pest of stored wheat and corn, presumably because so many of the grain kernels are damaged in transit and storage (often more than 25%), both by handling and by the infestation of primary insect pests.

Description. The adult is a reddish brown, oblong, flattened beetle, about 2 mm long. In adult specimens, sex can be determined by the length of the antenna and the shape of the prothorax. In the male, the antenna is nearly as long as the length of the body, whereas in the female, it is about two-thirds the length of the body. The male prothorax narrows slightly toward the posterior, whereas the female prothorax is nearly square. The adult *Cryptolestes pusillus* is a good flier. The egg is translucent, ellipsoid, and glossy white; its chorion lacks external sculpture. It is 0.5–0.6 mm long and 0.1–0.15 mm wide. The larva is white and elongated, with a flattened body and distinct head capsule; the posterior half of the body is slightly wider than the anterior half. The posterior tip of the body contains two anal hooks or horns. Mature fourth-instar larvae are 3.0–3.5 mm long. To prepare for pupation, the larvae build a tough, ovoid cocoon, which is made of silk and grain fragments. The pupa is semitransparent, white, and 2 mm long. The pupa can be sexed easily because the antennae in the female extend only to the prothorax, whereas in the male they reach the middle of the abdomen.

Similarities to other insects. Three species of *Cryptolestes* are commonly found in stored products in North America. The characters that follow can be used to distinguish them.

In adult *C. ferrugineus*, the head contains a ridge or sulcus above the eyes but lacks a transverse ridge near the dorsal posterior margin. The thorax narrows posteriorly (more in males than in females). In males, the accessory sclerite of the genitalia occurs as two crescents, with posterior lobes of the aedeagus strongly sclerotized. In females, the bursa copulatrix of the genitalia is semicircular in outline.

In fourth-instar larva, there is a more pronounced emargination of the posterior-dorsal margin of the head than that in *C. pusillus* and *C. turcicus*. The anal hooks are about 1.5 times as long as their combined width. In larva, the anal hooks are about twice as long as their combined width.

The head of *C. pusillus* contains a transverse ridge on the dorsal posterior margin. The ridge continues longitudinally anterior, dorsal to the eyes, diminishing ahead of the eyes. The thorax is wider than long (male thorax slightly narrowed posteriorly). On the elytra there are four rows of spines between the first and second, and the second and third elytral striae. In males, the accessory sclerite of the genitalia occurs as one crescent, with the posterior lobes of the aedeagus not sclerotized. In females, the bursa copulatrix of the genitalia is spiral in shape.

The head of *C. turcicus* contains a ridge on the dorsal posterior margin. The thorax is almost square; the hind angles, however, are acute and protruding (more in males than in females). The elytra has three rows of spines between the first and second, and the second and third elytral striae. Accessory sclerites of the male genitalia occur as two crescents. The apodeme of the ninth segment does not extend to the first abdominal segment. In larva, the anal hooks are twice as long as their combined width.

Physical limits and optimum rate of multiplication. The physical limits of development of *Cryptolestes pusillus* are 18–38°C, and 45–100% relative humidity. Optimum development occurs at 35°C and 90% relative humidity. The maximum rate of increase has also been reported to be 10 times per lunar month. The conditions giving maximum rate of oviposition are 32.5°C and 90% relative humidity.

Life cycle. Eggs are moist and deposited singly in loose food or in the crevices of the grain; food particles usually adhere to them. A female lays eggs, producing 20–334 in a lifetime. The rate of egg laying is about 0.5 eggs per day at 17°C and 4.0 eggs per day at 30°C. Egg production increases sharply with an increase in relative humidity from 50 to 90%. The mean duration (in days) of the egg, four larval instars (L1–L4), pupa, and egg-to-adult period of *C. pusillus* at 32°C and 90% relative humidity is as follows: egg, 3.5; L1, 4.0; L2, 3.6; L3, 3.3; L4, 7.0; pupa, 4.4; and egg to adult, 27.3. The mean longevity of males of this species at 90% relative humidity ranges from 48 weeks at 17.5°C to 16.1 weeks at 37.5°C. The comparable figures for females are 24.1 weeks at 17.5°C and 8.2 weeks at 37.5°C. The physical condition and nutritional quality of the food substrate also influence the duration of the life cycle. For example, when insects are reared at 28°C and 75% relative humidity on English wheat, the mean duration of the life cycle is 37.1 days, whereas on Canadian flour it is 43.4 days. Under adverse conditions, *C. pusillus* may show cannibalistic feeding behavior.

Ecology. *Cryptolestes pusillus* has been associated with hot spots in bulk-stored grain. Intensive larval activity in mixed-age populations can cause grain heating and excessive carbon dioxide production. Heavy infestations of several species of *Cryptolestes* are often associated with those of other major pests. Thus, in a survey of 60 grain farms in Queensland, Australia, in 1977–1978, species of *Cryptolestes* were found on 39 of the farms and 15% of the 483 samples taken. Ninety percent of infestations of *Cryptolestes* spp. were found in bag or bulk stores of seed and feed grain, where they were usually associated with heavy infestations of three more common stored-grain pests, *Sitophilus oryzae*, *Rhyzopertha dominica*, and *Tribolium castaneum*. *C. pusillus*, *C. ferrugineus*, and *C. pusilloides* were found on 45.6, 28.1, and 15.8%, respectively, of the farms.

Natural enemies. *Cryptolestes pusillus* larvae can be attacked by the tenebrionid predator *Palorus shikae* Sarup, Chatterji, and Menon. The following parasites attack *C. pusillus*: Sporozoa, *Mattesia dispora* Naville; Acarina, *Acarophenax* sp.; and Hymenoptera, *Plastanoxus westwoodi* Kieff. and *P. chittendenii* Ashm.

Order: Lepidoptera
Family: Tineidae

Nemapogon granella (Linnaeus)

Synonym: *Tinea granella* Linnaeus
Common names: European grain moth (wolf moth, maize moth, corn moth)

Economic importance. *Nemapogon granella* can be a serious pest of cereals, particularly wheat, barley, corn, and rye with high moisture content in elevators and warehouses. In grain elevators, this moth occurs in the basement, pits, boots, bin sides, chutes, and bins. Heavy infestation of this species lowers the quality of the grain by producing an off-odor, silky webbing, crusted areas along the bulk surface, and layers of tough and damp grain that may be heating; such grain is also contaminated by exuviae and frass from the insects.

Geographical distribution. *Nemapogon granella* is a common granary pest in the temperate regions of the world. It occurs frequently in Italy, Federal Republic of Germany, Poland, Sweden, the southern part of the USSR, Britain, and other European countries, as well as eastern parts of Canada, eastern and western coastal areas of the United States, and Argentina.

Climatic adaptability. *Nemapogon granella* is a moderately cold-hardy species that can develop at a temperature as low as 6.4°C. Although this moth species is an established granary pest in countries with cold climates, such as Canada and the USSR, *N. granella* infestation is generally restricted to the warmer parts of the grain-growing areas of these countries. It survives through the winter by hibernating or undergoing diapause in the full-grown larval stage. Exposure to winter cold, however, is necessary for its survival, because insect cultures that are kept at room temperature (20–22°C) during the winter die.

Food. *Nemapogon granella* feeds primarily on cereal grains and attacks the following cereals in decreasing order of preference: rye, wheat, barley, and oats. Other foods on which larvae can complete development are corn, soybeans, rice, almonds, hazelnuts, walnuts, peanuts, bran, grass seed, clover, flax, ergot, dry fruits, chocolate, mushrooms, seeds of ornamental plants, moldy cheese, wine-bottle corks, prunes, and chestnuts. On grain kernels, the larva feeds principally on the germ.

Type of damage and symptoms. In bulk grain, *Nemapogon granella* is usually a surface feeder (top 5–6 cm of a grain mass). During early stages of infestation, its presence is difficult to recognize until the appearance of excreta on the surface. As the larvae move from grain to grain and spin the grain kernels together with silken threads, clumps of grain and excreta are formed, and the grain–frass mixture produces a disagreeable odor. The formation of a webbing on the uppermost layer of the grain is a characteristic sign of infestation by this moth. To prepare for the winter, caterpillars often form cocoons in the timberwork of buildings. Consequently, their presence can be recognized only by careful inspection.

Description. The brightly colored adult has a 9–14-mm wing span. Its fore wings are silvery gray with dark brown, transverse stripes and a dark spot, and the hind wings are brown or gray with long hairs along the margin. The larva is 7–10 mm long, with a red brown head and yellowish white body, which is covered with short sparse hairs. The taxonomic characters of the larva include an adfrontal suture on the head reaching a vertical triangle, the front extending more than two-thirds to a vertical triangle. A prespiracular wart on the side of the prothorax has three setae. Seta IV of the first eight abdominal segments is behind the spiracle and seta V are below it; crochets on false legs are arranged in a single row and are of more or less same length throughout. The pupa is encased in a cocoon.

Similarities to other insects. The following species resemble *Nemapogon granella* (= *Tinea granella*): *Tinea cloacella* Haw., *T. ruricolella* Staint., *T. infimella* H.-S., and *T. salella* Zacher, but each can be separated by keys based on genitalia of each sex.

Physical limits and optimum rate of multiplication. The physical limits of complete development and multiplication are 7–27°C at 65–95% relative humidity. The optimum condition for development is about 25°C and 90% relative humidity. Complete development usually takes 70 days. All stages of *Nemapogon granella* die if the grain is kept below the freezing point or at 48–50°C for 1 hour. Insects do not attack wheat that has a moisture content below 14%.

Life cycle. The adults emerge in mid summer after overwintering as larvae; mating occurs a few hours after emergence, and egg laying begins after 2 days and lasts for 3–13 days. The number of eggs laid per female ranges from 29 to 218, with an average of 108. Eggs are usually laid singly. No more than two eggs are laid on a single seed, and eggs are also laid on bags, dust, and debris. The adult lives for 14–20 days, and can survive 11 days without food. The egg incubation period varies from 4–5 days at 25–27°C to 40–45 days at 11–12°C. The larva penetrates the grain and feeds first on the germ and then on the endosperm. In a laboratory study, the duration of the egg, larval, and pupal stages, which vary with temperature and relative humidity, were, respectively, 6, 45–58, and 8 days at 27°C and 90% relative humidity; 6, 64–92, and 8 days at 27°C and 65% relative humidity; 7, 30–52, and 10 days at 24–25°C and 90% relative humidity; 12, 50–73 and 15 days at 17–21°C and 90% relative humidity; and 14, 86, and 25 days at 15–17°C and 65% relative humidity. The pupal period usually lasts for 10–12 days in summer and 18–20 days in spring. In Canada and the United States, the life cycle is completed in about 10 weeks, and there are about two generations per year. In Swedish granaries, there is usually one generation and a partial second one per year; and the winter is passed in the larval stage. In spring, the overwintered larvae come out of the grain and pupate in cocoons in wall cracks, floors, and wooden material; the adult emerges 2–3 weeks later.

Ecology. The moths are active only at night. In countries with a temperate climate, such as the USSR, the first flight of the moth is observed early in spring (about April) after pupation of overwintered larvae either during autumn or spring. The second flight takes place during late summer (about August) from the generation of moths that emerged in the spring. The well-developed larvae of the second generation often overwinter under a sheltered web or in their cocoons. The larvae that failed to complete most of their larval developmental period remain in the top surface of the bulk grain and die as the grain cools with the onset of winter.

Natural enemies. Larvae of *Nemapogon granella* can be killed by its natural parasites, such as a mite, *Pyemotes ventricosus* Newport (Acarina). *N. granella* is a host of the following parasite wasps: *Nemeritis canescens* (Grov.), *Chremylus rubiginosus* Nees, and *Phygadeuon citinctus* (Geml.).

Order: Coleoptera
Family: Cucujidae

Oryzaephilus surinamensis (Linnaeus)

Common name: sawtoothed grain beetle

Economic importance. *Oryzaephilus surinamensis* is one of the most common insect pests of starchy food, such as stored cereal and cereal products on farms and in grain elevators, warehouses, and grocery stores. This species is often associated with heating of dry (14% moisture content) bulk cereals such as oats. In recent years this insect has increased in importance as a grain pest in Britain and other industrialized temperate countries, probably because of the widespread use of combine harvesting, which damages seed, and artificial drying, which provides a subtropical environment in granaries. Undamaged kernels of oats, wheat, and barley are immune to insect attack, unless they are moist and soft. Generally, the presence of dust, broken cereal grain, and dockage promotes infestation by *O. surinamensis* in warm and often freshly harvested grain. This species closely resembles a related species, *O. mercator*, which eats broadly similar foods. *O. mercator*, however, prefers oilseeds and their derivatives, such as palm products, cottonseed produce, and nuts. This species is more common in human dwellings than in outdoor granaries.

Geographical distribution. *Oryzaephilus surinamensis* has a worldwide distribution; it is common in areas of the world that are temperate or warmer. This species is one of the more common pests of stored grain and processed cereals in Canada, United States, Britain, Australia, Asia, Africa, and North and South America. Countries in which *O. surinamensis* is regarded as a major pest of wheat, corn, paddy, or other cereals include Cyprus, Czechoslovakia, Federal Republic of Germany, Iraq, Israel, Italy, Sweden, United Kingdom, and Australia. Because of the morphological similarity with *O. mercator*, the past distributional records of *O. surinamensis* sometimes represent either one or both species.

Climatic adaptability. *Oryzaephilus surinamensis* is both cold-hardy and tolerant of low relative humidity. It can overwinter in unheated buildings in Britain and some parts of Canada. The climatic plasticity index of *O. surinamensis* is 500 as compared with 210 for *O. mercator* and 570 for *Tribolium confusum*. In general, *O. surinamensis* is a highly adaptable insect pest of stored products.

Food. *Oryzaephilus surinamensis* feeds on various starchy foods but mainly cereal and cereal products. Some of the food it infests are stored oats, wheat, barley, rye, sorghum, rice, dried fruits, breakfast food, nuts, seeds, yeast, sugar, tobacco, candy, dried meats, corn, cornmeal, cornstarch, flour, pasta, milo, mixed feed, wheat bran, spices, herbs, nutmeats, bird seed, dog food, tea, and peas. It should be noted that because of a close resemblance between *O. surinamensis* and *O. mercator*, there has been misidentification in the past in North America and Europe; some of these records may not be reliable. Because *O. surinamensis* cannot penetrate dry, sound kernels, infestations often follow those of the granary and rice weevils, which are primary feeders of undamaged stored grain. When allowed to feed on broken kernels of wheat, oats, and barley for 10 weeks at 27°C, *O. surinamensis* multiplied over 10 times on oats and barley and six to seven times on wheat.

Type of damage and symptoms. Scarring and roughing of the surface of the food are indications of feeding by *Oryzaephilus surinamensis*. When found on a mass of whole grain, its presence indicates that either the grain was invaded earlier by other granivorous insects or the grain mass contains broken grain, weed seeds, dust, or other types of dockage, because this insect species does not feed on undamaged grain. When this insect penetrates packages of processed cereals, their contents become unpalatable and often unsalable. Heavy infestation of farm-stored grain, particularly oats, may cause heating. When overwintering bulk grain contains such an infestation, masses of beetles migrate to the bulk surface above the hot spot.

Description (Fig. 26). The adult is dark brown, flat, and narrow, about 2.5–3.0 mm long. The prothorax (the body part behind the head) of *Oryzaephilus surinamensis* has six distinct teeth on each side and three longitudinal ridges on the dorsal side. The adult is very active but rarely flies. The egg is white and shiny, about 0.85 mm long, three times as long as wide. The larva is elongate, brown-headed, white-bodied (pale yellow with darker plates on the dorsal surface of the segments when mature), six-legged, with the abdomen tapering to tip. A fully grown larva is extremely active, about 2.5 mm long. The larva forms a protective covering or pupal cell by sticking small food particles together and then clings with its posterior end to the inner surface of the cell. The pupa remains attached to the last larval skin. The pupa, which also has six teeth on each side of its prothorax, remains attached by its posterior to the inside wall of the pupal cell.

Similarities to other insects. *Oryzaephilus surinamensis* resembles *O. mercator* closely but can be differentiated from it by a comparison of the length of the "cheek" (temple) and the vertical diameter of the eye. *O. surinamensis* has smaller eyes and longer, rounded "cheeks" behind the eyes. The presence of teeth on the prothorax separates it from all other similar flat grain beetles that infest stored food.

Physical limits and optimum rate of multiplication. The range of temperature for development and reproduction of *Oryzaephilus surinamensis* is 18–37.5°C, with the optimum range at 31–34°C. The minimum relative humidity at which the insect can multiply is 10%. The maximum rate of increase per lunar month under optimum conditions is 50 times.

Life cycle. *Oryzaephilus surinamensis* lays eggs singly or in small groups on or near the food. Each female lays about 375 eggs during its lifetime. Eggs hatch at temperatures that range from 17.5 to 40°C; in 3–5 days they hatch at 30–40°C. Three larval instars are common, although the number of instars may range from two to five. Larval development is most rapid at 32.5°C and 90% relative humidity. The larval developmental period on wheat feed at 30°C and 30–70% relative humidity ranges from 12 to 15 days. The pupal period is about 1 week or longer. The life cycle from egg laying to adult emergence ranges from 20 days at 31–35°C and 65–90% relative humidity to 80 days at 21°C and 50% relative humidity and 100 days at 18°C and above 80% relative humidity. An adult may live as long as 3 years. The number of generations may be as high as one per month; four to seven generations per year is usual in the United States.

Ecology. *Oryzaephilus surinamensis* is well adapted to both indoor and outdoor conditions in both cool temperate and hot tropical areas of the world. It usually gathers in the moist and warmer parts of a grain mass. This species typically moves straighter and faster than *Tribolium castaneum*, *Sitophilus granarius*, and *Rhyzopertha dominica*. The activity of *O. surinamensis* increases in the evening, when many insects come to the grain surface. In southern Ontario and Western Canada, *O. surinamensis* can take advantage of the warm weather of the harvest season and multiply rapidly in bulk-stored grain of 12–14% moisture content with some dockage, allowing the grain to sustain hot spots if it is left undisturbed through the winter. The postharvest, autumn invasion of farm granaries by *O. surinamensis* is usually followed by heavy infestation of *Cryptolestes ferrugineus* in the winter. As the grain temperature and moisture content rise as a result of successive breeding of these two insect species, the grain ecosystem may be invaded successively by fungus beetles, such as *Ahasverus* and *Cryptophagus*; mites, such as *Kleemannia* and *Acarus*; and microorganisms, such as *Penicillium*, *Aspergillus*, *Absidia*, and *Streptomyces*. Suddenly a population explosion occurs, manifested by about a tenfold increase of insects and mites, after which the hot spot usually dries and cools. The arthropod infestation is restricted to the top 30 cm of the bulk, whereas microorganisms infect the entire grain mass. The grain below the hot spot becomes drier during winter, which limits downward migration of the arthropod species from the hot spot. In spring the insects spread from their overcrowded quarters to the warm and moist top layers of the surrounding grain mass. Initiation of hot spots by *O. surinamensis* depends mainly on the availability of favorable warm air temperature and adequate breeding time in the autumn. *O. surinamensis* is also a common pest of dried raisins in the Mediterranean basin, southern Australia, and California. In raisins stored for a year or more it becomes most abundant in the spring, but its numbers decline considerably during the hottest months.

Natural enemies. A common predator of *Oryzaephilus surinamensis* larvae is a hemipteran, *Xylocoris flavipes* (Reuter). It is not very effective in controlling the prey species. *O. surinamensis* is a well-known host of at least two parasitic wasps: *Holepyris sylvanidis* (Brethes) and *Cephalonomia tarsalis* (Ashmead).

Order: Lepidoptera
Family: Pyralidae

Plodia interpunctella (Hübner)

Common names: Indianmeal moth (driedfruit moth)

Economic importance. *Plodia interpunctella* is a troublesome and destructive pest of stored products, particularly stored cereals, dried fruits, peanuts, and processed foods in granaries, warehouses, groceries, confectionaries, and households in many parts of the world. Webbing, excreta, and frass in infested products are often a nuisance. In Canada, this species can cause serious infestations of stored products in large warehouses and grain elevators in southern Ontario and in coastal cities. In the United States, it is one of the most common and important pests of stored corn and peanuts. In India, its outbreaks are sudden and short-lived, and less common than those of *Ephestia cautella*. In the USSR, it is a secondary pest of cereal products, but it causes damage to dried fruit and stored medicinal herbs. In the food industry, the destructive activities of *P. interpunctella* encompass a wide variety of foods and confectionary items. In infested bulk-stored grain, the top layer is often thickly matted with silk webbing intermixed with frass, pupal cases, and numerous dirt-covered white crawling larvae. This layer of grain is usually completely spoiled.

Geographical distribution. *Plodia interpunctella* is reported to have originated in the Old World, and it now has a cosmopolitan distribution. Because of its preference for corn, it is common in the corn-growing and corn-storage areas of Canada and the United States. Some other countries from which *P. interpunctella* has been reported as a pest are United Kingdom, France, Federal Republic of Germany, Switzerland, Japan, Korea, India, and Australia.

Climatic adaptability. *Plodia interpunctella* is a cold-hardy species but it requires moderate relative humidity to develop. It seems to do well in regions with mild temperate climates. This species can overwinter in unheated granaries in Britain and in parts of Canada and the United States. The following periods of exposure to cold will kill all stages: –3.9 to 1.1°C for 90 days; –6.7 to –3.9°C for 28 days; –9.4 to –6.7°C for 8 days; and –12.2 to –9.4°C for 5 days. At the other extreme, an exposure of 52°C for 6 hours kills all stages; at 40°C adult emergence from pupae is suspended. *P. interpunctella* is not as adaptable as some other common stored-product moths. It has a climatic plasticity index of 330 as compared with 600 for *Ephestia kuehniella* and 575 for *E. cautella*.

Food. *Plodia interpunctella* is a primary feeder of not only cereals, nuts, and dried fruits, but also of most other dry foods found in households and groceries. Great diversity of its food preference is shown by the following list of foods it has been known to infest: corn, wheat, rye, barley, rice, millet, oats, milo, rolled oats, peanuts, pulses and pulse products, beans, chocolate, nut bars, biscuits, raisins, dried apples, packaged breakfast cereal, spices, powdered milk, dried roots, herbs, dead insects, pollen in bee hives, drugs, alfalfa hay, almonds, almond hull meal, bread, canary grass seed, cantaloupe seed, chili pepper, copra, cotton seed meal cake, dried prunes, garlic, iris rhizomes, lettuce seed, dried meat scraps, mixed feeds, orange pulp, peas, pecans, pepper seed, popcorn, pumpkin seed, rice hulls, rolled barley, mealed corn germ, sunflower seed, soybeans, sugar beet pulp, vetch seed, walnuts, hazelnuts, watermelon seed, chicory roots, and wheat germ. Some preharvest and postharvest seedborne fungi are also used as food.

Type of damage and symptoms. In grain bins and elevators, *Plodia interpunctella* infestation is restricted to the top 20 cm. The grain kernels along the surface are often held together by a mat of silken webbing containing frass and larval skins. In infested bagged feed or other cereal products, larvae move through the product, leaving a dirty trail of webbing and excreta. White silken cocoons containing the pupae are seen along the sides or outside such bags. When feeding on wheat or other cereals, *P. interpunctella* prefers germ, bran, and endosperm, in that order. In chocolate bars with almonds and other nuts, the insects are more attracted to the aroma of the nuts than to the chocolate content.

Description (Fig. 27). The adult moth, which has a 13–18-mm wing span, is characterized by the color pattern of its fore wings. The basal half of the fore wings is gray, whitish, or pale straw yellow with occasional dark spots; the remaining outer part (as well as the head and thorax) is reddish brown, with a coppery sheen and faintly visible darker transverse, irregular, leaden gray stripes. The hind wings are grayish white. At rest, the wings are folded closely together into the shape of a roof along the line of the body, and the antennae (two-thirds the body length) lie flat on the wings. The egg is 0.3–0.5 mm long, ovate, and grayish white; its surface has a granular texture that diffracts light in many colors. The first-instar larva is about 1 mm long. The full-grown larva is 10–13 mm long with a dirt-covered, whitish body and a pale yellow and reddish brown head. Depending on the food the larvae consume, some may be pinkish brown or greenish. Five to six eye spots are on each side of the head. The front on the head extends slightly more than two-thirds to a vertical triangle. The prespiracular wart has two setae; sclerotized rings occur around setae III of the mesothoracic and the eighth of the 10 abdominal segments. Setae of the first to seventh abdominal segments arise from indistinct pinacula. In the larva, the third to the sixth and the tenth abdominal segments each bear a pair of short prolegs. Mature pupae are 6–11 mm long, light brown, with a glossy surface, whereas younger ones are straw-colored. The pupae are usually encased in silken cocoons, but occasionally they can be naked. Mutant forms are common among *Plodia interpunctella* populations; one such form lacks normal color pattern and has uniformly dark fore wings.

Similarities to other insects. *Plodia interpunctella* can be easily distinguished from other closely related stored-product moth species, such as *Ephestia kuehniella* and *E. cautella*, by the palpi, which extend forward horizontally with a tuft of scales that make a beaklike cone about the length of the head; in the other two moth species the palpi are erect.

Physical limits and optimum rate of multiplication. The physical limits for successful development and multiplication of *Plodia interpunctella* are approximately 18–33°C and 25–95% relative humidity, the optimum being 26–29°C and 70–75% relative humidity. The maximum rate of increase is 30 times per lunar month.

Life cycle. The adult *Plodia interpunctella* begins mating 1 hour after emergence, usually in darkness. The female produces a sex pheromone which attracts males and facilitates mating. A female deposits 40–400 eggs (average 170) singly, in chains, or in clusters on the larval food; oviposition is usually completed within 4 days after mating. Adults live for 5–13 days. Eggs hatch in 2–17 days. The larval period that includes five instars ranges from 13 to 288 days. Most fully grown larvae spin a cocoon in which to pupate. The pupal period lasts for 4–33 days (average 15). Development from egg to adult takes about 26 days (range, 24–31 days) at 30°C and 70% relative humidity and 39 days (range, 35–46 days) at 30°C and 25% relative humidity on a mixture of wheat feed, yeast, and glycerol (10:1:2). At low temperatures (below 20°C) and under other adverse conditions, some of the larvae of certain strains enter into diapause, or a prepupal resting stage, thereby prolonging the length of the life cycle. Diapause usually occurs when individuals are subjected to one of the following conditions: continuous darkness or photoperiods of different lengths, depending on the geographical strain during larval development; incubation of eggs at a temperature above 30°C; or incubation of late-instar larvae at 20°C or lower. During diapause, the respiratory metabolism of the insect is greatly reduced, usually rendering the fumigants used for its control ineffective. Adults emerging from cocoons in cracks of walls, storage boxes, or food avoid light and rest quietly in dimly lit parts of the house, flying in a zigzag manner when disturbed. Generally, they fly most actively shortly after dusk until almost dawn. There are four to six generations per year.

Ecology. In heated premises, *Plodia interpunctella* feeds and multiplies continuously. At low winter temperatures, the insect overwinters through the larval stage (or in diapause) and resumes its life cycle in the spring, if the weather is favorable. On the West Coast of the United States, where it undergoes five generations (some of which are overlapping), it has two complete generations, two partial summer generations, and one winter generation. When infestations are heavy, the surface of bulk grain becomes covered with a thick blanket of larval webbing, under which the larvae feed. This silken blanket protects immature forms from unfavorable temperature and relative humidity as well as from the attacks of hymenopterous parasites. In Canada, partly grown cold-resistant larvae overwinter on the walls or ceiling of the bin, beneath the bin floor, or on the grain-handling equipment. After pupation in summer, the first group of adult moths emerge in the middle of June, mate, and lay eggs. About three generations are common in Ontario and British Columbia during summer and early autumn. Generations are characterized by the presence of many larvae, followed by the presence of many moths and few larvae. The presence of an enormous larval population marks the last generation. As they mature, such larvae leave the grain and search for a place to pupate.

Natural enemies. The most common endoparasite of *Plodia interpunctella*, which accompanies most of its outbreaks, is a small brachonid parasite, *Bracon hebetor* Say. This parasite has a high rate of natural increase and it can effectively control moth populations. Other known parasites of *P. interpunctella* are *Dibrachys cavus* (Walker), *Venturia canescens* (Grav.), *Microbracon brevicornis* Wesm., *Mesotenus gracilis* Cres., *Horegenes kiehtani* Dier., *Apanteles nephoptericis* Pack., and *Nosema* spp. This moth is also adversely affected by a granulosis virus disease.

Order: Lepidoptera
Family: Pyralidae

Pyralis farinalis **(Linnaeus)**

Synonym: *Pyralis meridionalis* Schmidt
Common names: meal moth (meal-snout moth, grain snout moth)

Economic importance. *Pyralis farinalis* occurs in bulk grain in bins, elevators, warehouses, and grain ships, where it feeds and multiplies on grain and grain products that are damp, damaged, and slowly deteriorating. This species characteristically occurs in patches of moldy grain. It is a pest of secondary importance in flour mills and grain elevators, but on occasion it can become a primary pest of seed stored in cool and damp areas. The presence of this insect usually indicates a poor state of sanitation and a lack of preventive and control measures in granaries, elevators, and mills. It is more common in the silos and screens in provender mills than in the milling section of flour mills. *P. farinalis* can also attack and seriously damage lucerne and clover hay.

Geographical distribution. *Pyralis farinalis* is a cosmopolitan species, but it is more common in temperate regions than in tropical ones. Some countries where it has been reported as a pest include Canada, United States, United Kingdom, Bulgaria, Yugoslavia, Greece, Italy, Poland, USSR, Egypt, South Africa, U.S. Virgin Islands, New Zealand, Australia, Japan, and India.

Climatic adaptability. *Pyralis farinalis* is a moderately cold-hardy moth that can overwinter and thrive during warm months in unheated farm granaries across the Prairie Provinces of Canada and the cool grain-growing areas of the United States and the USSR. It is less adapted to the warmer climatic zones of the world.

Food. *Pyralis farinalis* is primarily a feeder of moldy and decaying cereal and cereal products with a high moisture content. The larval food of this moth includes wheat, barley, oats, corn, corn refuse, peas, navy beans, flour, bean cakes, flower bulbs (tulips, for example), peanuts, dry chicory roots, dried fruits, potatoes, almond hulls, cotton gin trash, cotton seed, mixed feed, sunflower seed, and wheat bran.

Type of damage and symptoms. *Pyralis farinalis* prefers damp and deteriorating flour and moldy grain; it may severely damage sound cereals and their products when the moisture content of the food and the relative humidity of the air are high. *P. farinalis* larvae can cause 99% mass loss of wheat kernels by eating bran, germ, and endosperm, leaving only traces of kernel and abundant amounts of webbing. Undamaged kernels are eaten only when they have more than 22% moisture content. Larvae are able to cut holes in burlap bags, seriously damaging them and allowing the grain to spill. Old stocks of bagged grain products stored in damp locations may be severely damaged by this species. The large colonies of *P. farinalis* larvae can be recognized by large lumps of the infested product (usually a moldy mass) attached together by a thick network of larval webbing. Definite evidence of infestation by this moth in grain bins is invariably heavy webbing along the top surface of the bulk grain.

Description. In adult moths, the fore wings are dark brown (occasionally chocolate-colored) and light brown across the middle; the light and dark brown areas are separated by transverse wavy white lines; a row of black dots line the posterior margin. The smoky black hind wings are crossed by two narrow white lines. The wingspan is about 25 mm (range, 15–28 mm). The larvae are dirt-covered, gray or whitish, with head and the first body segment (prothoracic shield) black. The posterior tip of the body is tinged with orange. The main larval taxonomic characters include the front (on head) extending slightly less than half-way to a vertical triangle; median adfrontal suture almost equaling epicranial suture in length; and four distinct ocelli. The prespiracular wart has two setae. Dorsal and ventral setae on the first to seventh abdominal segments are without distinct pinacula; group VII seta of ninth abdominal segment is represented by a single seta. Posterior area of abdominal spiracles is twice as thick as, or thicker than, anterior area; biordinal crotchets are present; larger crotchets are three to four times as long as smaller ones.

Similarities to other insects. Although they belong to the same family and share similar stored-food habitats, adult *Pyralis farinalis* can be easily distinguished from *Plodia interpunctella* by the larger size, characteristic wing coloration, and sitting pattern of *Pyralis farinalis*. The resting moth folds its wings in the form of a triangle, with the end of the abdomen bent downward.

Physical limits and optimum rate of multiplication. Physical limits and optimum rates of multiplication of this species are not known. *Pyralis farinalis* develops and reproduces well at 27–30°C and 70–80% relative humidity.

Life cycle. Female moths lay an average of 250 eggs (range, 200–500) in the food material. As the larvae develop and molt, they spin tough silk tubes that are glued to grain kernels or food particles in clusters. When fully grown, the larvae come out of the tubes and spin cocoons in which to pupate. Pupal cocoons also contain food particles. The life cycle is completed in 6–8 weeks during summer in Canada and the United States. Adult moths live for 1–3 weeks. Generally, there are one to two generations per year in North America. In the southern parts of the USSR, as many as four generations per year may occur. Overwintering occurs in the larval stage.

Ecology. In a humid environment (for example, basements and other cool, damp places where there are moist grain products or debris) that contains damp cereals or cereal products, *Pyralis farinalis* can multiply and build up a large population in a short time. Large populations can be maintained for several seasons if undisturbed. Webbing and foodstuffs from mutilated bags are usually found where the bags touch one another or along the seams of sewn bags. When *P. farinalis* has a two-generation cycle in the American midwest, the summer generation is short and the autumn generation needs a prolonged hibernation and development period.

Natural enemies. The chief natural enemy of *Pyralis farinalis* is a chalcid parasite, *Tetrastichus* sp., which can greatly reduce the field population by parasitizing the larvae. *P. farinalis* is a host of the following parasitic wasps: *Microbracon (Habrobracon) hebetor* Say, *Metacoelus mansuetor* (Grace), and *Barichneumon anator* (F.).

Order: Coleoptera
Family: Curculionidae

Sitophilus granarius (Linnaeus)

Common name: granary weevil

Economic importance. Well-known from ancient times, *Sitophilus granarius* is a highly domesticated primary pest of stored wheat, rye, barley, and most other whole cereals, mainly in the cool temperate parts of the world. It prefers a cooler climate than does *S. oryzae* and *S. zeamais*. Infestation by *S. granarius* causes a reduction in seed quality through weight loss. Losses resulting from secondary invasion of seeds by fungi and bacteria, a subsequent rise in free fatty acids, and occasional grain heating are common.

Geographical distribution. *Sitophilus granarius* has a cosmopolitan distribution but is most common in Europe and countries with a cool temperate Mediterranean type climate, such as the northern part of North America and the USSR, Europe, and Japan. Countries where it is considered the major pest of wheat and other cereals include Cyprus, Czechoslovakia, Federal Republic of Germany, Iraq, Italy, Paraguay, Poland, South Africa, Sweden, and Spain. In warm climates, it occurs at high altitudes as are found in Kenya, Ethiopia, Afghanistan, and Pakistan. In South America, it occurs in cooler areas of Argentina and Bolivia.

Climatic adaptability. *Sitophilus granarius* is cold-hardy, particularly in areas that have a high relative humidity for part of the year. It attacks grain in areas with continental climates, especially where winters are cool, but not severe. *S. granarius* has a climatic plasticity index of 173 as compared with 570 for *Cryptolestes ferrugineus* and 275 for *S. oryzae*. After gradual cold-temperature acclimation, it can feed on damaged kernels of wheat at 4.4°C. It can also move and survive at 1.7–4.4°C for 111 days and at –1.1 to 1.7°C for 73 days. It has adapted well in the type of climate found in southern Ontario (Canada), midwestern France, or southeastern Australia.

Food. *Sitophilus granarius* feeds on whole stored cereals such as wheat, barley, rye, corn, sorghum, rice, cowpeas, acorns, chestnuts, sunflower seed, and bird feed. Solid foodstuffs of cereal origin, such as caked flour, are also used as insect food and substrate for egg laying. Generally, *S. granarius* does not develop in millet, oilseeds, and pulses, with the exception of chickpeas. Loose-flour materials are unsuitable for larval feeding or development.

Type of damage and symptoms. Seed damage can be recognized by small circular holes in seeds through which the adult emerges from inside the seed, where it spends all its immature stages. During its development as a larva, *Sitophilus granarius* consumes 30 mg of grain, leaving 6 mg of debris. In the course of completing development on a single wheat kernel at 30°C and 70% relative humidity, *S. granarius* consumes 64% of the kernel, destroying all the germ and a large part of the endosperm. To develop, a single insect uses 79 calories from a 126-calorie wheat kernel and the adult uses a further 284 calories during its nearly 100-day lifetime. *S. granarius* can reproduce three to four times as quickly on whole wheat and barley as on whole oats at 30°C and 70% relative humidity.

Description (Fig. 28). The adult is a shiny, dark reddish brown to black weevil, about 2.5–4.7 mm long. Its head is telescoped into a distinct snout-like prothorax almost as far as the eyes. Its two feelers (geniculate cirri) are bent abruptly like a bent knee and are located at the base of the snout. The tip of the snout is equipped with a pair of strong jaws (mandibles). The top of the thorax and upper wings are covered with deep longitudinal punctures that form rows of depressions with short hairs. The lower wings are too poorly developed to allow the weevil to fly. Adult weevils can be sexed by examining the snout (rostrum) in the male, which is comparatively rougher, shorter, and wider than that of the smoother, longer, and more slender snout of the female; the abdominal sternites 5 and 6 in the male project downward, unlike those of the female. The oval, yellowish eggs are 0.6–0.7 mm long and 0.3 mm wide. The white larval body is shortened with a protuberant back, covered with deep, transverse folds. A comparison of the width of the brown head capsule is the best way to separate the four instars of legless larvae or grubs. For *Sitophilus granarius*, the mean width and range (in parentheses) of the head capsule at each instar is as follows: I, 0.25 mm (0.20–0.28); II, 0.35 (0.35–0.39); III, 0.51 (0.42–0.58); IV, 0.68 (0.60–0.76). The full-grown larva, which is about 3–4 mm long, changes into a white or light brown pupa and then to a brown adult.

Similarities to other insects. To an untrained eye, various *Sitophilus* species found in stored grain look similar. The adults of *S. granarius*, however, can be easily separated from those of *S. oryzae* and *S. zeamais* by the elongated punctures on the thorax; the adults of the other two species have round or irregularly shaped punctures. In addition, *S. granarius* lacks the four reddish spots that occur on the wing covers of *S. oryzae*; when disturbed, both *S. granarius* and *S. oryzae* feign death by drawing their legs up close to the body, falling, and remaining motionless.

Physical limits and optimum rate of multiplication. The minimum temperature and relative humidity for successful development are 15°C and 50%, respectively; optimum conditions are 26–30°C at 70% relative humidity. Its maximum rate of multiplication per lunar month is 15 times. *Sitophilus granarius* populations (Australian strains) can survive and multiply at 15°C; but the capacity of increase is correlated with its fertility at 27°C, which is an optimum temperature. The length of exposure required to give complete kill of adults (hardiest stage) of

S. granarius varies from about 1 day at –15°C to 58 days at 0°C when the grain moisture content is about 14%. The weevil, however, can live as long as 100 days at 0°C when the moisture content of the grain is increased to 18%. *S. granarius* is less tolerant of short exposures of supraoptimal temperatures (40°C) than is *S. oryzae* at 13–14% moisture content, except when the former is acclimated for several generations at 30°C.

Life cycle. The female lays a single egg on a single wheat kernel (two or three eggs on corn) in holes excavated in each kernel and then seals the opening with an adhesive liquid that hardens to form a mucilaginous egg plug on top of the egg as the ovipositors are withdrawn. The number of eggs laid by a single female in a lifetime can be 100–400. The larval development, occurring through four instars inside the kernel, takes about 19–34 days. The range of average duration of the immature stage in days at 25°C and 70% relative humidity is as follows: egg, 4.5–5; total larval stages, 22–24.5; pupa, 8–16; preadult, 5; and total immature stages, 37–43. The newly emerged adults may remain inside the kernel for 5 days at 25°C and for up to 80 days at 12.5°C. Maternal age of the weevils affects the developmental period; the older the mother is, the longer is the developmental period of the offspring. The life cycle, from egg laying to adult emergence, under favorable conditions ranges from 28 to 43 days. The length of the life cycle and the number of generations per year depend on temperature and moisture content of the breeding environment as reflected by the seasons. In heated granaries, the weevil can breed year round, producing up to five generations per year. The number of generations per year in various parts of the world is as follows: southern parts of Canada and northern parts of the USSR, one; southern parts of the USSR, two; and eastern parts of the United States, four. Although the longevity of *Sitophilus granarius* has been reported to be up to 432 days, most studies show that it lives for about 100–182 days.

Ecology. *Sitophilus granarius* can create hot spots in stored grain, raising grain temperatures to 40°C and facilitating the invasion of other secondary stored-grain insects, mites, postharvest fungi (*Penicillium*, *Aspergillus*), and bacteria. *S. granarius* can be the dominant primary species, feeding voraciously and increasing rapidly during the early stages of succession of insect species in infested bulk grain; but they seem to disappear abruptly after they have consumed the damaged seed. Although, these weevils are often found in moldy grain, particularly during the advanced stages of their infestations, they do not consume large quantities or multiply on common seed-borne fungal species, except for *Nigrospora sphaerica* (Sacc.) Mason, and *Curvularia tetramera* (McKenny) Baedijou. Dispersion of this species is governed mainly by touch (thigmotactic response); individuals move away from excessively dry grain. During heavy infestation, disturbance from crowding forces this species of weevil to move up towards the surface, where individuals then move along the boundaries and are little affected, within certain limits, by changes in temperature and relative humidity. Isolated individuals move in an irregular pattern. Females are more active in the evening, and when disturbed they tend to move upward. Fungi have a neutral effect on the accumulation of

S. granarius. Physical disturbance of larvae frequently prevents them from successfully completing development. About 95% mortality is common when grain falls from a 14 m height, as when it is augered from one bin to another. In flour mills, contamination of grain with *S. granarius* is restricted to processing locations before the screen sections, because sound grains are required for egg laying and larval development. In the USSR, *S. granarius* can breed in warm granaries throughout the year, producing up to five generations per year. Under natural conditions in the southern grain-growing areas, two or three generations are produced per year, whereas one or two are produced in the central areas. Its preference for relatively warm breeding temperatures (25–27°C) restricts its abundance in the central and particularly the northern part of the USSR. The weevils avoid light and barely tolerate very dry grain (8% moisture content or less). In bulk grain they gather in the warmest parts, and during prolonged storage, along the top 1–1.5 m of the bulk. The weevil remains absolutely still when the infested part of the bulk grain is slightly disturbed. But a live weevil can be distinguished from a dead one by the position of the legs and antennae—in dead beetles they project sideways.

Natural enemies. *Sitophilus granarius* is a host of several facultative parasitic wasps, such as *Anisopteromalus calandrae* (Howard), *Choetospila elegans* Westwood, *Dibrachys cavus* (Walker), and *Lariophagus distinguendus* (Foerster).

Order: Coleoptera
Family: Curculionidae

Sitophilus oryzae (Linnaeus)

Synonyms: *Calandra oryzae*, *Sitophilus sasakii*
Common name: rice weevil

Economic importance. *Sitophilus oryzae* is universally regarded as one of the most destructive primary pests of stored cereals such as rice, wheat, barley, and corn. It does not often breed in noncereal foods, although it does attack split peas or pasta. It can attack cereal plants in the fields. Voracious feeding of whole grains by this insect causes weight loss, fungal growth, and quality loss through an increase in free fatty acid and can even completely destroy stored grain in all types of storage. Invasion by this primary pest may cause grain heating and may facilitate the establishment of fungal colonies, secondary insect pests, and mite pests.

Geographical distribution. *Sitophilus oryzae* is cosmopolitan, but is found more commonly in warm tropical and subtropical areas than in temperate regions. Countries in which *S. oryzae* is a major pest of cereals are Argentina, Australia, Central African Republic, People's Republic of China, Colombia, Cyprus, Czechoslovakia, Egypt, India, Iraq, Israel, Italy, Japan, Kenya, Lebanon, Libya, Mozambique, Paraguay, South Africa, Botswana, Dominican Republic, Somalia, Burma, Malaysia, United States, USSR, Kenya, Nigeria, and Zambia.

Climatic adaptability. *Sitophilus oryzae* is moderately cold-hardy but requires relatively high relative humidity to develop. It is most common in the tropical and warm temperate zones of the world but usually does not extend into cooler areas. It does not thrive in areas with extremely high summer temperatures and is often displaced in moist and hot regions by a closely related species, *S. zeamais*. *S. oryzae* has a climatic plasticity index of 275, as compared with 700 for *Tribolium castaneum* and 173 for *S. granarius*. In the midwestern United States, the weevil produces four or five generations per year; in the Crimean Peninsula and the southern regions of central USSR, four to seven generations per year are common, whereas in the northern grain-growing areas, such as northern Caucasus, the number of generations drops to two or three per year. In Canada it usually occurs in southern Ontario, where it is likely to have one generation per year.

Food. Generally, both adults and larvae feed on whole cereal grains, including wheat, rice, barley, corn, groundnuts, cassava, beans, millet, and sorghum; but the females can lay eggs and develop on solid products made of cereals, such as pasta. *Sitophilus oryzae* can infest maturing grain, especially corn in the field, in the southern United States and in other tropical regions.

Type of damage and symptoms. The legless *Sitophilus oryzae* larvae feed and develop inside the grain kernel undetected from outside. With their strong jaws, the larvae chew large irregular holes in the germ and endosperm of the kernel. After emerging from the pupa, the adult exits through a circular hole about 1.5 mm in diameter and attacks new kernels. Irregularly shaped holes on seeds characterize *S. oryzae* infestation. Two rice weevils may develop at the same time on two sides of a single kernel. A single insect can destroy about 30% of a wheat kernel in the development from egg to adult. An individual insect consumes 47 calories from a 126-calorie wheat kernel in the course of its development from egg to adult and in the first 50 days of adult life at 30°C and 70% relative humidity. In a heavy infestation, the only part of a grain that remains is the shell of the kernel perforated by adult feeding and emergence holes. Damage to sorghum kernels during harvesting and handling makes it more susceptible to rice weevil attack.

Description (Fig. 29). The adult is 2.5–4 mm long, reddish brown or dark brown, with a long narrow snout containing strong, chewing mouth parts and eight-segmented, elbowed, club-shaped antennae. The adults of *Sitophilus oryzae* and *S. zeamais* can be easily separated from those of *S. granarius* by the presence of the round closely spaced punctures (instead of oval, as in *S. granarius*) on the thorax and two reddish brown areas on each wing cover (elytron). Only the internal character of the male, such as the sculpturing of the aedeagus (penis), can be used to separate the first two species: in *S. oryzae*, the upper surface of the aedeagus is evenly convex and in *S. zeamais*, it is flattened and has two distinct longitudinal impressions. Other life stages can be seen only by dissecting an infested kernel. Eggs are shiny, white, opaque, and ovoid to pear-shaped. The larva is white, stout, and legless and spends all its instars inside the kernel. Measurement of head capsule widths of slide-mounted larvae under a stereomicroscope is the best way of separating the four larval instars. For *S. oryzae*, the mean and range (in parentheses) of the head capsule widths of the larval instars (I–IV), in millimetres, are as follows: I, 0.22 (0.18–0.27); II, 0.32 (0.28–0.36); III, 0.47 (0.38–0.57); and IV, 0.66 (0.58–0.80). The pupa is also white but it contains (pressed against its body) legs, wings, and the snout of the fully grown adult.

Similarities to other insects. *Sitophilus oryzae* is almost identical in external characters to *S. zeamais* (see "Description"). However, *S. oryzae* rarely flies, whereas *S. zeamais* frequently flies. *S. oryzae* seems to prefer smaller grains, such as rice, and *S. zeamais* prefers larger grain, such as corn. Although the seed damage caused by the Angoumois grain moth, *Sitotroga cerealella*, is similar to that of the rice weevil, the two types can be distinguished by the form of the adult emergence holes on infested seeds and the presence of adult feeding damage in cases of *S. oryzae*.

Physical limits and optimum rate of multiplication. Physical limits for successful development are 17–34°C and 45–100% relative humidity; optimum conditions are 26–31°C at 70% relative humidity. The activity of this insect ceases at about 40°C. It multiplies 25 times per lunar month. *Sitophilus oryzae* is less susceptible to high temperature than is *S. granarius*.

Life cycle. The female chews a hole on a selected site on the kernel, either in the field or in storage; she then deposits a single egg and seals the opening with a gelatinous plug, which when hardened is called the egg plug. A female lays two or three eggs per day and between 300 and 576 eggs in a lifetime. After hatching, the larva feeds, develops through four instars, and pupates inside a single kernel. The average duration of life stages in days at 25°C and 70% relative humidity are as follows: egg, 4–6.5; total larvae, 18.4–22.0; pupa, 8.3–14.0; preadult, 3; and total immature stage, 34.1–40.0. Life cycle from egg laying to adult emergence at 70% relative humidity requires 26 days at 30°C, 43 days at 21°C, and 96 days at 18°C. At 21°C and 70% relative humidity the first appearance of each larval instar (I–IV) and pupae, in days after egg laying, is as follows: I, 6; II, 13; III, 17; IV, 24; pupa, 34; and adult emergence, 43. Adult longevity is about 7–8 months, and occasionally up to 2 years.

Ecology. Laboratory studies have revealed that *Sitophilus oryzae* shows a characteristic dispersal behavior in the grain mass. Its migration rate is higher from a dense population than from a light population. In bulk wheat with 14% moisture content and stored at 30°C, *S. oryzae* disperses only slightly from the spot at which it is introduced, regardless of the position of this spot. The insects move away quickly only when the temperature rises to 32°C or higher. It has been suggested that loose packing of grain, thereby enlarging the volume of intergranular airspace, facilitates insect movement.

In its response to temperature, light, and relative humidity, *S. oryzae* becomes photonegative when placed in a dark–light environment at 25°C and 34% relative humidity, but gradual decrease in the relative humidity (6–72 hours) lowers the intensity of the photonegative reactions, and the insect's response becomes photopositive. *S. oryzae* is a poor flier as compared with *S. zeamais*.

In interspecific competition with *S. zeamais* reared in both wheat and corn at 29°C and 70% relative humidity, *S. oryzae* was the more productive species in wheat, and *S. zeamais* in corn. When *S. oryzae* is reared with *Rhyzopertha dominica* in various cultivars at 30°C and 70% relative humidity, *S. oryzae* usually becomes the superior and more productive species. In bulk-stored grain, which is a poor heat conductor, heat produced by the respiration of *S. oryzae* is not readily dispersed. Consequently, temperature rises in the infestation pocket, producing positive feedback for the thriving insect. The rising temperature accelerates both the development rate and the oviposition rate, so that the population growth rate also rises sharply. Additional moisture produced by greater metabolic activity of life stages also speeds up population growth. Eventually, optimum temperature and moisture content are reached, and the insects begin to disperse from this self-made hot spot, which by now is also contaminated with storage fungi (e.g. *Aspergillus*, *Absidia*), actinomycetes, and bacteria. Such dispersion enlarges the area of infestation and often the hot spot. When the temperature rises to 40°C or more at the core of the hot spot, many insects are killed. The surviving migrant adults, having moved to more favorable parts of the habitat, continue the breeding process and sustain the abnormal temperature levels of the hot spots. The enlarging boundary of hot spots becomes restricted only when it comes in contact with the edge of the bin or a sharply defined front of cold grain.

Natural enemies. *Sitophilus oryzae* is a host of the following hymenopterous wasps: *Anisopteromalus calandrae* (Howard), *Choetospila elegans* Westwood, *Holepyris sylvanidis* (Brethes), *Lariophagus distinguendus* (Foerster), *Cephalonomia tarsalis* (Ashmead), *Cerocephala dinodiri* Graham, *Meraparus requisitus* (Tucker), and *Dibrachys cavus* (Walker). These parasites, however, have limited potential as agents of biological control.

Order: Coleoptera
Family: Tenebrionidae

Tenebrio molitor Linnaeus

Common name: yellow mealworm

Economic importance. *Tenebrio molitor* is the largest insect pest of stored cereal and milled cereal products and is commonly found in moist environments in elevator boots and floors, disused spouts, and mill stocks. Such stocks are usually left undisturbed for some time in flour and feed mills, warehouses, and other grain-storage premises. Yellow mealworm frequently occurs in moist cereals, and cereal products at various stages of decomposition. *T. molitor* larvae are often sold commercially in pet shops as food for ants, birds, amphibians, reptiles, carnivorous arthropods, fish, and animals in zoological parks. Because it is not a primary feeder of cereal grains, this species does not cause serious damage in granaries and flour mills; its presence, however, is an indication of poor sanitation in an area where cereals and cereal products are stored.

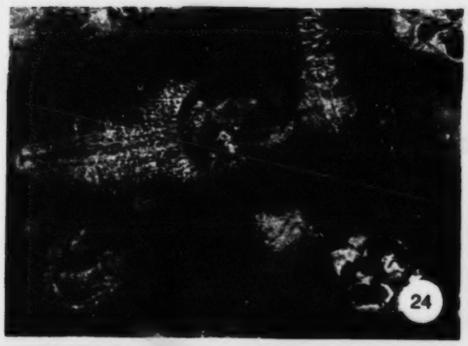
Geographical distribution. *Tenebrio molitor* is cosmopolitan in distribution and probably European in origin. This species has been a common pest of flour mills, warehouses, and grain elevators in Canada and the northern United States for more than a century.

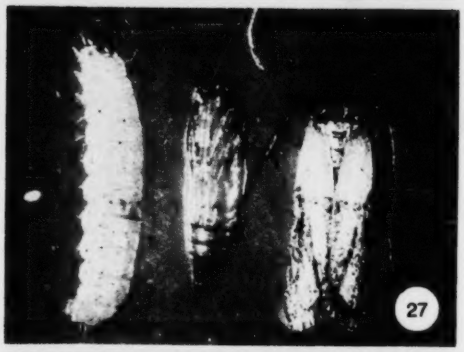
Climatic adaptability. *Tenebrio molitor* prefers a cooler climate than a related species, *T. obscurus*. *T. molitor* reproduces freely in the humid continental climate of the northern United States and southeastern Canada. It is a cold-hardy species that overwinters in the larval stage in unheated buildings (3–10°C) in Northern Ireland, Britain, Eastern Canada, and the United States.

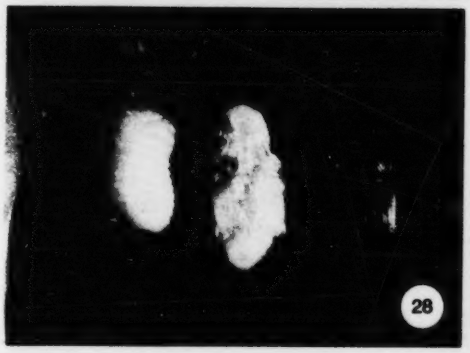
Food. *Tenebrio molitor* is a scavenger and prefers to feed on decaying damp organic debris made up of grain or milled cereals that are left undisturbed in dark neglected corners of mills and warehouses. It also feeds on flour, meal, bran, cereals, bread, crackers, mill sweepings, meat scraps, feathers, bodies of dead insects, dried fruit, nuts, porridge, and biscuits.

Type of damage and symptoms. An infestation of *Tenebrio molitor* can be recognized by the tracks left by the large, crawling larvae on undisturbed flour and grain dust on the floor. When fully grown, larvae can crawl up the walls of the granary. Bread prepared from flour that has been previously infested for 1–3 months with *T. molitor* has a relatively low baking quality; a "chemo-phenolic" taste and odor are detected in such bread. Flour and milled cereals infested with these conspicuous insects often have a disagreeable odor. Such foods are generally rejected for aesthetic and assumed health reasons.

Description (Fig. 30). Adult beetles are robust, flattened, shiny black or dark brown, 14–18 mm long, with fine grooves on wing covers. The antenna has the apical segment as long as it is broad, and the third segment is only slightly (1.2:1) longer than the fourth. Eggs are oblong-oval, opaque, milky white, shiny, 1.75–1.80 mm long and 0.60–0.70 mm wide. An egg is often difficult to find because of a coating of dust or flour particles adhering to its sticky surface. The newly emerged larvae are white and 2–2.5 mm long. They turn yellowish brown or honey yellow as they feed and grow. Fully developed larvae are bright yellow, shading to yellowish brown toward each end and at the junction of each segment. A mature larva is 26–30 mm long with a cylindrical body about 10 times as long as it is broad. Pupae, which lack a pupal case, are white at first and then turn yellow to yellowish brown; they are 14–19 mm long and 5–7 mm wide.







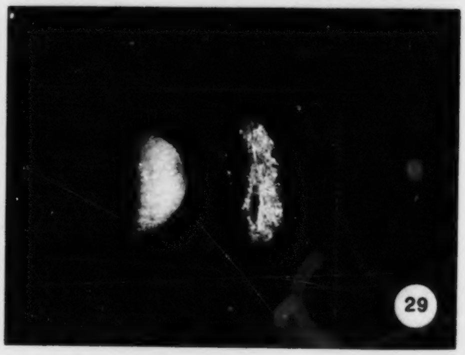


Fig. 24 Wheat kernels infested by *Cryptolestes ferrugineus*.

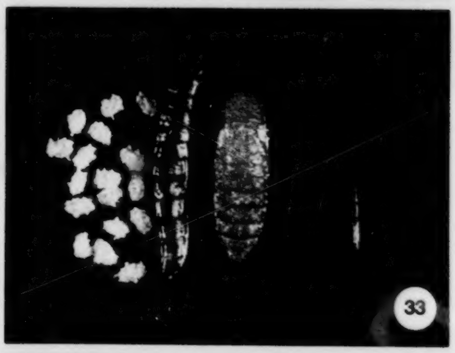
Fig. 25 Life stages of *Cryptolestes ferrugineus* (left to right): eggs, larva, pupa, and adult.

Fig. 26 Life stages of *Oryzaephilus surinamensis* (left to right): egg, larva, pupa, and adult.

Fig. 27 Life stages of *Plodia interpunctella* (left to right): egg, larva, pupa, and adult.

Fig. 28 Life stages of *Sitophilus granarius* (left to right): egg, larva, pupa, and adult.

Fig. 29 Life stages of *Sitophilus oryzae* (left to right): egg, larva, pupa, and adult.



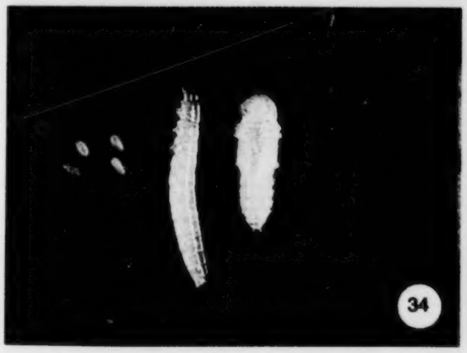


Fig. 30 Life stages of *Tenebrio molitor* (left to right): eggs, larva, pupa, and adult.

Fig. 31 Larva of *Tenebroides mauritanicus* on wheat kernels.

Fig. 32 Wheat kernels infested by *Tribolium castaneum* adults.

Fig. 33 Life stages of *Tribolium castaneum* (left to right): eggs, larva, pupa, and adult.

Fig. 34 Life stages of *Tribolium confusum* (left to right): eggs, larva, pupa, and adult.

Fig. 35 Life stages of *Tribolium madens* (left to right): eggs, larva, pupa, and adult.

Similarities to other insects. *Tenebrio molitor* is similar to the dark mealworm, *T. obscurus*. A *T. molitor* larva can be easily distinguished from that of other species by its yellow color. Another distinguishing character is the apical segment of the antenna, which is as long as it is broad in *T. molitor* and broader than long in *T. obscurus*.

Physical limits and optimum rate of multiplication. *Tenebrio molitor* multiplies at 18–30°C and 60–95% relative humidity. It is usually reared in the laboratory at 25–30°C. *Tenebrio molitor* larvae are both cold-hardy and highly resistant to desiccation. They can survive for a long time in extremely dry situations. During desiccation, they remain in a state of dormancy.

Life cycle. The adult male and female mate within 2–5 days after emergence. Females lay their eggs for 22–137 days at a rate of up to 40 eggs per day; an average of 276 eggs (maximum 600 eggs) are laid in a lifetime. Adults live for about 2 months. The egg incubation period ranges from 4 to 19 days. The larval development period ranges from 281 to 629 days and the number of larval instars ranges from 7 to 20 (9–19 is common), depending on temperature, food supply, crowding, and other environmental factors. The larvae can withstand starvation for several months. The onset of pupation appears to be triggered by increases in temperature that accompany a change of season—winter to spring or spring to summer. The pupal period ranges from 6 to 18 days, also depending on the season. Normally, there is one generation per year, but the life cycle may be extended to as long as 2 years.

Ecology. *Tenebrio molitor* thrives in dimly lighted or totally dark environments of undisturbed damp and decaying grain masses. In Eastern Canada, it is more common and abundant in wheat and wheat debris in grain elevators, flour mills, and feed mills. It is commonly found in equipment boots, along walls, and on floors of granaries. *T. molitor* females excite and attract males with the aid of a sex pheromone. The mating and related activities of this species are initiated by several chemical signals (pheromones), which coordinate the reproductive behavior of both sexes of the species. The best characterized pheromone is an attractant that is released by females and acts only on males; the male also produces a smaller quantity of this attractant immediately after emerging as an adult, but this rate of pheromone release increases markedly after the first 5 days of adult life. Two distinct types of male pheromones are known: an excitant that attracts females and an antiaphrodisiac that inhibits the response of other males to female scent. Cold-acclimated (3–14°C) *T. molitor* larvae are capable of greater dispersal at low temperatures than warm-acclimated (30–33°C) larvae.

Natural enemies. A stored-product mite, *Caloglyphus mycophagus* (Megnin), has been reported to be a predator of *T. molitor*.

Order: Coleoptera
Family: Trogositidae

Tenebroides mauritanicus (Linnaeus)

Common names: cadelle (bolting cloth beetle, bread beetle)

Economic importance. *Tenebroides mauritanicus* is one of the largest and most well-known primary insect pests that attack stored grain and its products. It is an important pest in rice, warehouses, flour mills, and farm granaries. Its larvae burrow into the wooden structure of empty farm granaries and remain in their galleries until the arrival of newly harvested grain. Both larvae and adults feed on grain germ, flour, bran, and the immature forms of other stored-product insects. In flour mills it can gnaw through the silk cloths of sieves, bolting reels, and redressing machines. The residual stocks of grain and grain debris at the bottom of elevator boots, particularly on wooden premises, are favorite spots for the breeding of these insects. Wooden walls and floors of all types of grain storage—railway boxcars, grain boots, or old wooden elevator bins—are also common sites of infestation by *T. mauritanicus*.

Geographical distribution. *Tenebroides mauritanicus* has been known to be a destructive pest of stored wheat in Europe since 1758. The species spread to North and South America in the 19th century and has become a cosmopolitan pest. Grain-carrying ships of the past, which contained wooden structures in their holds, were the best carriers of these beetles. Some of the warmer geographical areas where it is found are Europe, North and South America, Africa, Indonesia, Hawaii, Australia, southern USSR, Brazil, India, Egypt, Turkey, Seychelles, Nigeria, and Taiwan.

Climatic adaptability. *Tenebroides mauritanicus* is a cold-hardy species. The adults and all stages of larvae (often in hibernation) can overwinter in unheated warehouses and granaries in England and the United States and can survive for several weeks at subzero temperatures. The eggs and pupae are readily killed by cold. It has been suggested that *T. mauritanicus* can occur in flour mills in regions of the world that have a hot damp climate, characterized by temperatures above 22°C and relative humidity above 70%. Exposure to 49–54°C kills all stages of this species in about an hour.

Food. Both adult and larval stages of *Tenebroides mauritanicus* feed on stored products of plant and animal origin. Generally, they attack the germ or the soft parts of the seed. Sometimes the adults are predacious and feed on other stored-product insects. *T. mauritanicus* infests rice, cotton seed, sorghum, cassava, potatoes, cinnamon, nutmeg, palm and cocoa seed, almond, beet pulp, milo, mixed livestock feed, Sudan grass seed, cornmeal, packaged ground cereal, breakfast foods, biscuits, bread, pearl barley, bran, semolina, and tobacco. It also eats larvae and frass of other insects found in stored-grain products. In old flour mills with poor sanitary conditions, *T. mauritanicus* can cut holes through the silk of sieves as it feeds on milling stocks in the machines. In Europe, it is often found under the bark of trees and in rotten wood, where it is predaceous on small wood-feeding insects. In the past, it was frequently carried into grain elevators and grain bins as larvae and pupa in wood used for building and construction.

Type of damage and symptoms. Because *Tenebroides mauritanicus* is among the largest of stored-product insects, the presence of its large larvae or their tracks on food particles and dust can be easily recognized. This insect causes much damage by gnawing through paper packages and bags and even through wooden boards. The insect's large entry holes, which also facilite the entry and escape of other smaller stored-product insects to and from food containers, can be easily seen. Abandoned holes often serve as reservoirs for grain debris that harbors other insects. The larvae usually feed on the grain germ or embryo and cause seed damage. Larvae can destroy large quantities of grain and grain products and can contaminate the food with larval skins cast from several moltings.

Description. The adult is flattened, oblong, elongate, and about 6.5–11 mm long (usually 8–11 mm). The beetle is dark brown to black with a smooth, shiny back. Its thorax is considerably drawn out and separate from the abdomen, creating a constricted "waist." The eggs are white and opaque, elongate, spindle-shaped (often curved), about 1.2–1.5 mm long and 0.25–0.35 mm wide. The larva (Fig. 31) is white to grayish white, soft-bodied, and fleshy, with a conspicuous black head, black spots on three thorax segments just behind the head, and two short dark horns (hooks) attached to a plate at the posterior end of the body. A full-grown larva can be up to 17 mm long. The pupa is white, elongate, about 7–10.5 mm long and 2.5–3.5 mm wide. It often remains hidden inside holes burrowed by larvae into wood or in cracks and crevices. Sexes can be separated by the characters of the pupal genital papillae: male with two slight protuberances; female protuberant, three-segmented and divergent.

Similarities to other insects. *Tenebroides mauritanicus* adults resemble *Tenebrio molitor* because of their large size and dark color, but *T. molitor* is larger, more robust, and lacks the constricted waist between thorax and abdomen characteristic of *Tenebroides mauritanicus*.

Physical limits and optimum rate of multiplication. Physical limits for survival of *Tenebroides mauritanicus* lie somewhere between –9°C and 40°C. Exact limits, which depend on acclimation and genetic factors, are not known. The larvae and adults of this species are highly resistant to low temperature, although locomotor activity ceases at 3–12°C. The lower limit for successful multiplication is about 15°C. Favorable conditions for development and reproduction are 28–30°C and 70–80% relative humidity. The rate of increase is slow (one to two generations per year) because of prolonged developmental time and hibernation in winter.

Life history. The adult female deposits 10–60 (usually 20–30) eggs, one batch at a time, loosely in flour or in the crevices of infested food. The oviposition period ranges from 2 to 14 months and the number of eggs laid ranges from 430 to 1319. In one case, 3581 eggs were laid by a female fed on a mixture of oatmeal, yeast, and fungi in the laboratory. The egg-to-adult development period ranges from 70 to 400 days, and the number of larval instars from three to seven, depending primarily on food and temperature conditions during rearing. Longevity of the adults, particularly the females, ranges from 6 to 22 months. Under adverse conditions (hibernation or inadequate nutrients, as in tobacco), the larval period can be prolonged up to 36 months. One generation per year (occasionally two) is common when the insects occur in unheated granaries in temperate countries; up to three generations per year can occur in tropical countries.

Ecology. In North America, larvae and adults, which live in the open, especially under tree bark and in the mines of wood-boring insects on which they prey, are active in winter and only hibernate at low temperatures; eggs and pupae die in cold winter months. Adults emerging in late autumn live longer (about 12 months) than those emerging in spring (about 6–7 months). At 15°C adults can withstand starvation for up to 114 days and larvae for up to 33 days. The nutritional value of the food greatly influences the development and abundance of *Tenebroides mauritanicus*. For example, at 30°C, the life cycle was completed in whole wheat in 79 days, in whole wheat flour in 90 days, in white flour in 102 days, and in raw rice in 96 days. In fluctuating temperatures, the life cycle was completed between 106 and 124 days, depending on food. *T. mauritanicus* occurs in flour mills and feed mills in the hot, damp climatic regions of Africa and Asia and in hot, damp premises in temperate countries.

Many *T. mauritanicus* are found in all seasons in samples of whole grain, processed foods, floor sweepings, debris from corners and between floor boards, grain dust, and machinery in feed and flour mills in the coastal cities of North America. The population fluctuations are largely dependent on the temperature changes in the microenvironment. Overwintering and residual larval and adult populations of *T. mauritanicus* in old wooden farm bins can quickly infest newly stored grain in these bins.

Natural enemies. *Tenebroides mauritanicus* larvae may be parasitized by *Dibrachys cavus* (Walker) and *Nosema* spp. *T. mauritanicus* is a well-known predator of larvae of several stored-product insects including *Plodia interpunctella*, *Oryzaephilus surinamensis*, and *Tenebrio molitor*. It is hypothesized that *Tenebroides mauritanicus* does not aggressively attack these insects, but its carnivorous diet is often essential for the completion of its life cycle.

Order: Coleoptera
Family: Tenebrionidae

Tribolium audax Halstead

Common name: American black flour beetle

The black species of *Tribolium* collected from North America for over a century and previously identified as *T. madens* was shown in 1969 by D.G.H. Halstead to be distinct from the true *T. madens* of the Old World. *T. audax* is smaller, less convex and more elongate than *T. madens*, and the two species do not interbreed. The true *T. madens* is not as common in North America as in Europe.

Economic importance. Although still occurring in forests under tree bark (e.g. *Pinus ponderosa*, *P. monticola*) and in bee nests, it has now established itself as a moderately successful pest of stored cereals and their products on farms and in warehouses and flour mills in North America. *Tribolium audax* infests farm-stored wheat, corn, and oats and their products. Heavy infestation of wheat flour by this species gives an unpleasant odor to the flour, lowers the baking quality, and spoils the taste of bread made from it.

Geographical distribution. *Tribolium audax* is well-adapted to both the oceanic and the continental temperate climates of North America. It has occasionally been reported from the warm and dry southern states of New Mexico and Texas in the United States.

Climatic adaptability. *Tribolium audax* is well-established in regions of North America that have a climate that is either oceanic or continental temperate. It appears to overwinter in unheated granaries in these regions. Because of its occasional incidence in the southern United States, *T. audax* may also become adapted to subtropical climates.

Food. *Tribolium audax* feeds on farm-stored cereals and their products. It has been reported in corn, wheat, barley, oats, flour, cells of leaf-eating bees, beehives, animal foods, and the bark of pine trees. In its natural habitat, it can feed on insect larvae (Bibionidae) in logs in the forest.

Types of damage and symptoms. Damage done to cereal grain and flour by *Tribolium audax* is generally similar to that done by two closely related species, *T. confusum* and *T. castaneum*. Bread made from flour infested by *T. audax* has an undesirable "quinone" (2-methyl and 2-ethyl-1,4-benzoquinones) taste and odor.

Description. Adult beetles are 2.8–4.5 mm long and 1.0–1.6 mm wide, moderately depressed, dull, dark brown, with antennae and legs lighter. Larvae resemble those of *Tribolium confusum*, but the color of the tergites in *T. audax* is very dark brown. The beetles move rapidly but they rarely fly.

Similarities to other insects. *Tribolium audax* closely resembles *T. madens*. The various life stages of the two species can be distinguished by the characters given for *T. madens* in this book.

Physical limits and optimum rate of multiplication. The physical limits for development have not been established for *Tribolium audax*, which can complete development at 21–35°C and 50–70% relative humidity.

Life cycle. Females lay eggs singly, directly on foods. The mean egg-to-adult development period is 80 days at 21°C ± 1°C and 50% relative humidity and 41 days at 30°C ± 0.5°C and 56% relative humidity. *Tribolium audax* reared at 32°C and 70% relative humidity completes development in 43 days and attains full maturity in 50 days. Its longevity ranges from 68 to 97 days in males and 69 to 94 days in females when the insects are reared in a mixture of whole wheat flour and yeast (19:1) at 35°C and 60% relative humidity. *T. audax* can develop well and can complete its life cycle on dockage-free whole wheat at 27–33°C and 70% ± 2% relative humidity; the presence of 2–10% dockage (broken grain, dust, weed seeds) in whole wheat does not improve the rate of adult emergence.

Ecology. Little ecological data are available on *Tribolium audax*, although its association with leafcutting bees, *Megachile* spp., is well known. *T. audax* occurs in bee nests, which often serve as a natural reservoir of stored-product insect pests, such as some other species of *Tribolium*.

Natural enemies. In the laboratory *Tribolium audax* cultures are often heavily infected with a sporozoan endoparasite, such as *Farinocystis tribolii* Weiser or *Lymphotropha tribolii* Ashford. Their infection can cause heavy mortality to the host insect species.

Order: Coleoptera
Family: Tenebrionidae

Tribolium castaneum (Herbst)

Synonym: *Tribolium ferrugineus* Herbst
Common names: red flour beetle (rust red flour beetle)

Economic importance. *Tribolium castaneum* is one of the most well-known and common stored-product insects infesting cereals, oilseeds, and other vegetable and animal products in all types of granaries, elevators, mills, and warehouses throughout the world (Fig. 32). Because it cannot feed on undamaged, dry seed with less than 12% moisture content and confines its attack to grain dust, broken grain, and milled stocks, *T. castaneum* is often considered a secondary pest of stored grain and called a "bran bug." Nevertheless, the importance of this species is enormous in terms of variety of stored products attacked, climate adaptability, flying ability, omnivorous feeding behavior, and an unusually high intrinsic rate of natural increase.

Geographical distribution. *Tribolium castaneum* seems to have originated in the Indo-Australian region and is recorded to have invaded human habitats since the time of the Pharaohs in Egypt, circa 2500 B.C. From its Old World origin, this species has been widely scattered by humans, and it is now considered a cosmopolitan species. It is a major pest of stored grain and its products in Canada, United States, United Kingdom, Europe, Mexico, Argentina, Brazil, USSR, Ghana, Zambia, Malawi, Kenya, India, Burma, and Australia, among other countries.

Climatic adaptability. Climatically, *Tribolium castaneum* is one of the world's most well-adapted and successful insect pests of stored grain. Although it is relatively cold-susceptible compared with the cold-hardy *Cryptolestes ferrugineus*, *T. castaneum* is a well-established grain pest in the cold Canadian prairies. Partly because of its unusual tolerance for low humidity (minimum relative humidity 1%), it is a pest in the semiarid regions of the world, such as Egypt, Sudan, and Niger. *T. castaneum* can also thrive in middle latitude humid lands (Western Europe, USSR, People's Republic of China, and Japan), particularly those with a humid continental climate and long summers. Of the 51 stored-product insect species considered for their environmental adaptive ability (plasticity index), *T. castaneum* showed the highest climatic plasticity index, 700, as compared with 570 for *T. confusum* and 275 for *Sitophilus oryzae*.

Food. *Tribolium castaneum* is an omnivorous and cannibalistic insect. Its larvae and adults feed on the embryo of seed, grain dust, broken grain, and dockage. Some of its foods are wheat, corn, barley, millet, flax, sunflowers, rapeseed, milo, rye, peanuts, oilseed cakes and their products, alfalfa seed, copra meal, cotton gin trash, cotton seed, cotton seed meal, beans, peas, ginger, dried plant roots, dried fruits, nuts, sago, rice, rice and wheat bran, pulses, flour, food spices, cayenne pepper, chocolate, snuff, cocoa beans, English walnuts, almonds, baking powder, soyflour, soy grits, orrisroot, yeast, milk powder, insect collections, and packaged processed foods from all types of cereals, oilseeds, and pulses. Adults and larvae are also cannibalistic, particularly in crowded situations, where they feed on the eggs and pupa (occasionally larvae) of their own species. *Tribolium castaneum* feeds voraciously and reproduces on common seedborne fungi of the genera *Alternaria*, *Mucor*, *Cladosporium*, *Nigrospora*, *Absidia*, *Curvularia*, and *Scopulariopsis*. Although the presence of dockage or damaged seeds is crucial for its feeding under suboptimum conditions (27°C), *T. castaneum* can feed and multiply well on dockage-free wheat in optimum environmental conditions (70% relative humidity and 33°C).

Type of damage and symptoms. Food stocks infested by *Tribolium castaneum* show many reddish brown beetles moving over the material when they are disturbed (Fig. 32). The larvae feed on the inside of the cereal seeds that are often initially damaged by a primary granivorous insect, such as *Sitophilus oryzae*. Heavily infested flour turns grayish and contains cast skins, fecal pellets, and frass. Flour may turn pink, giving out a disagreeable taste and odor caused by a volatile, yellow or reddish brown liquid secreted by the scent glands of the adults living on the food.

This secretion is composed of 2-ethyl-1,4-benzoquinone, 2-methyl-1,4-benzoquinone (toluquinone), 2-methoxy-1,4-benzoquinone, and an oily secretion of molecular weight 179. Levels of free fatty acid and uric acid in infested flour increase as the thiamine content decreases. The potential baking quality of flour infested longer than a month is lowered by the brittleness of gluten, poor flavor, and bitter taste of the bread. Bread made from wheat flour heavily infested for 1–3 months with *T. castaneum* progressively shows darkening of the crumb, reduced loaf volume, color variation, and a distinct offensive taste and odor. Wheat infested with *T. castaneum* for 2 months shows significant increases in fat acidity and decreases in germination and microfloral levels, particularly those fungal species of the *Aspergillus glaucus* group and *Penicillium* spp. Because of destruction of the germ by insect feeding, infested wheat undergoes rapid germination loss. From a 126-calorie wheat kernel, 60 calories are consumed by a single *T. castaneum* during development from egg to adult in a 20-day period.

Description (Fig. 33). Adults are 2.3–4.5 mm in length, with an elongate body, and reddish brown to blackish. The adult body is relatively flat, with a pronotum that is broader than long; the sides of the abdomen are parallel. The eleven-segmented antenna has three terminal segments forming a pronounced club. The eyes are not elevated, they are partly divided by a posteriorly produced side margin of the head and they have three or four facets at the narrowest point. Generally, one or more of external segments four through seven are strongly elevated from base to apex. The adult male can be separated from the adult female by the presence of a subbasal setiferous puncture on the ventral side of the anterior femur; such a puncture is absent in the female. Eggs are 0.6–0.7 mm long, 0.3–0.4 mm wide, white or transparent, oblong, with a viscous surface to which flour particles adhere. The whitish yellow larval body is elongated and cylindrical, with short yellow hairs on the head and body, and about eight times as long as it is wide. *Tribolium castaneum* larvae can be separated from those of some other beetle genera by the two-pointed end of the last body segment (cercus). The length of the first-instar larva is about 1.1 mm, and the width of the head capsule is 0.2 mm. The pupa is white, 3.3–3.4 mm long, 1.1 mm wide, and weighs about 2.4–2.5 mg.

Similarities to other insects. Adults of *Tribolium castaneum* closely resemble those of *T. confusum* and to a lesser extent the other two closely related *Tribolium* species, *T. audax* and *T. madens*, which can both be distinguished by their black color. *T. castaneum* adults can be distinguished from those of *T. confusum* by the characteristics that follow.

T. castaneum is a strong flier; the last three antennal segments abruptly increase in width to form a club; the eighth segment is half as wide as the ninth; no ridge over the head projects over the eye; the eyes are bigger than those of *T. confusum*; they seem transversely oval and their width is equal or nearly equal to that of the area between them when observed from below; and an extension of the head divides one-third the length of the eye in the middle.

T. confusum is a nonflying insect; the last three antennal segments gradually increase in width; the eighth segment is slightly narrower than the ninth; the ridge on the head projects slightly over the eye; the eyes are smaller than those of *T.*

castaneum; they seem rounded, and their width is about one-third that of the area between them when observed from below; and an extension of the head divides half the length of the eye in the middle.

Pupae of *T. castaneum* and *T. confusum* can be separated by the characters that follow.

In *T. castaneum*, the eyes are only partly divided in the middle; the lobes on each side of the abdomen contain two hairs, with one longer hair located on the larger anterior lobe and one shorter hair located one-third the distance from the posterior edge.

In *T. confusum*, the eyes are almost completely divided, and the lobes on each side of the abdomen contain three hairs, the longest one located on the anterior lobe and the two shorter ones on tiny medium lobes.

Physical limits and optimum rates of multiplication. The physical limits of successful development and multiplication are 20–40°C and 10–95% relative humidity; the optimum ranges are 32–35°C and 70–75% relative humidity. The maximum rate of increase of *Tribolium castaneum* under optimum laboratory conditions is 70 times per lunar month.

Life cycle. The female lays about 450 eggs at random on the food substrate. The egg hatches into a slender larva in 2.6–13.9 days, within a temperature range of 20–40°C (2.6–3.6 days at 30–40°C). The relative humidity does not affect the length of the egg period. The larval period, which may include 5–11 larval instars, ranges from 12.0 to 109.0 days, depending on temperature, relative humidity, and food (12–15.3 days at 30–37.5°C and 90% relative humidity). The optimum temperature for larval development on crushed wheat is about 35°C. At every temperature, larvae develop most quickly at the highest relative humidity. The active larvae avoid light and live within the food substrate. The pupal period requires 3.9–24 days at 20–37.5°C and 3.9–5.5 days at 30–37.5°C. The mature larvae usually pupate above the surface of the food substrate or in cracks or crevices. The total developmental period from egg to adult is approximately 20 days under optimum conditions, but this period can be prolonged, depending on the nutritive value of the food and physical conditions such as temperature and relative humidity. For example, on the preharvest fungus *Nigrospora sphaerica* at 31°C and 70% relative humidity, the egg-to-adult development period is 30 days compared with 22 days on a mixture of wheat flour and brewer's yeast (19:1). Adults have been known to live for as long as 335–540 days in the laboratory. In warm tropical climates or under uniform laboratory conditions, *Tribolium castaneum* can breed throughout the year; under favorable conditions four or five generations per year are common.

Ecology. In warm weather, *Tribolium castaneum* flies (up to 90 cm above ground) and spreads from one storage area to another. The insects show increased activity at night. In a warehouse they migrate to the surface of the bags from inside the contained food. During afternoons in tropical countries, adults show an urge to climb upward and to fly; the urge to fly seems to be related to temperature.

T. castaneum has been found in ripe corn in the field in the warm southern United States. It shows a distinct dispersal behavior unlike some other stored-grain beetles, which stay inside the grain mass. *T. castaneum* often occurs on the surface of stored grain but will gather within the bulk where broken grain, dust, or dockage have accumulated. Growth of postharvest storage fungi, such as those of the *Aspergillus glaucus* group and *A. candidus*, favors the accumulation of *T. castaneum* in damp grain pockets. Although often considered a tropical pest, *T. castaneum* can invade farm-stored grain during warm fall harvest weather in temperate countries. The insulating property of the grain, combined with the insect's high rate of increase, allow this species to multiply quickly in grain that is often harvested at about 36°C on hot summer days and stored for the winter in large farm granaries. Metabolic heat generated by thriving insect populations may, under certain circumstances, create hot spots with temperatures of up to 42°C, causing serious grain spoilage.

It has been estimated that monthly mean temperatures of 20°C or higher in grain stored in a small insect-infested farm bin (with a capacity of about 13 t) for at least 4 months could set up a serious infestation by *T. castaneum*. Of course, warmer harvest temperatures (27°C and higher) are required to start the initial infestation pocket. *T. castaneum* is often associated with primary grain feeders, such as *Sitophilus granarius* and *S. oryzae*, or grain germ-feeders, such as *Cryptolestes ferrugineus*. The feeding damage caused by other insects facilitates the increase of a *T. castaneum* population, and this species competes successfully with both whole-grain insects and germ-feeding insects. In the United States, it is more common in the south than elsewhere.

Natural enemies. The following arthropods are known to be ectoparasites of *Tribolium castaneum*. Of these the most common is a mite, *Acarophenax tribolii* (Newstead and Duvall), which clings to the host bodies of all stages of the insect and gets its nourishment from the insects; the gravid female mites destroy many beetle eggs. Nevertheless, mites are of little significance as agents of effective biological control. The other parasites of *T. castaneum* are *Pyemotes* (*Pediculoides*) *ventricosus* Newport, *Blattisocius tarsalis* (Berlese), *Rhabdepyris zeae* Turner and Waterston, and *Holepyris sylvanidis* (Brethes). *T. castaneum* also has several sporozoan endoparasites, e.g., *Adelina*, *Farinocystis*, and *Nosema*, which may seriously affect the survival and well-being of the insect population.

Order: Coleoptera
Family: Tenebrionidae

Tribolium confusum Jacquelin du Val

Common name: confused flour beetle

Economic importance. *Tribolium confusum* has been associated with human habitats since 2500 B.C. It is one of the most common and harmful insect pests of prepared and processed cereal products, particularly in flour and feed mills, warehouses, and retail stores. It is a secondary grain feeder that does not feed on undamaged cereal seeds but attacks all types of damaged, broken grain, milled products, and flour and grain dust, causing millions of dollars of damage every year. Popularly known as a "bran bug", this species is most common in the production buildings of mills and bakeries, where cereal products are processed and stored, and in shipments of grain and grain products.

Geographical distribution. From its presumably African origin, *Tribolium confusum* has been transported in various farinaceous foods by humans and is now cosmopolitan in distribution. Because of its relatively high tolerance for low temperature, *T. confusum* seems to occur more frequently at higher latitudes than do other storage species of *Tribolium*. It is a common flour-mill pest in the temperate climate of Mediterranean countries, Canada, United States, United Kingdom, and Europe. Countries in which *T. confusum* is considered a major pest of cereal products include Cyprus, Paraguay, Spain, USSR, South America, Australia, Japan, and People's Republic of China.

Climatic adaptability. Although *Tribolium confusum* is a moderately cold-hardy insect species favoring a temperate climate, it can rarely survive the winter in unheated structures in England or Canada. In the laboratory, all stages of *T. confusum* die after exposure at 7°C for 22–25 days; –1.1°C for 17 days; –3.9°C to –1.1°C for 12 days; –6.7 to –3.9°C for 5 days; and –9.4 to –6.7°C for 1 day. Nevertheless, *T. confusum* is one of most climatically adaptable stored-product insects; it has one of the highest climatic plasticity indices, 570, among the stored-product insect species studied.

Food. Adults and larvae of *Tribolium confusum* feed on a wide variety of foods, such as wheat feed, wheat flour, bran, rice flour, rye flour, corn meal, barley flour, rolled oats, spices, chocolate, nuts, snuff, ginger, peas, beans, dried fruits, tobacco seeds, slippery elm, almond meat, beet pulp, breakfast cereal, weevil-damaged cereal, sunflower seeds, cotton seed, cotton seed meal, mixed feeds, powdered milk, rice, safflower meal, vetch seed, walnut meat, brown and milled rice, rice screenings, and brewer's rice. When *T. confusum* is present in whole grain, its larvae attack the grain.

Type of damage and symptoms. Adult beetles are easily seen in even moderately infested foods; the larvae construct tunnels during their movement through flour and other powdered food. The insects release gaseous quinones from their glands, which give a identifiable, disagreeable, sour smell. Flour heavily infested with *Tribolium confusum* produces a dough that does not rise as readily as that from uninfested flour. Other characteristics of bread made from infested flour are color variation, reduction of loaf size, presence of a distinct, offensive bitter taste, and offensive odor.

Description (Fig. 34). The adult *Tribolium confusum* is a shiny, flattened oval, reddish brown beetle, 2.6–5.0 mm long and 1.2–1.3 mm wide. The average lengths and widths, respectively, of the three body parts of female are head, 0.82 and 0.46 mm; thorax, 1.16 and 0.88 mm; and abdomen, 1.26 and 2.56 mm. The extended body of *T. confusum* has a thorax (pronotum) that is broader than long and an abdomen with parallel sides; the head and upper part of the thorax are densely covered with minute punctures. The eleven-segmented antennae are gradually thickened towards the apex to form poorly differentiated clubs of five segments. The margins of the eyes are distinctly elevated, and the narrowest part of the strongly divided eye is no broader than one or two facets. Elytra have first and second intervals flat or at most carinate only at the apex. The females are slightly larger than the males. The egg is white with a sticky external surface, 0.58–0.74 mm long and 0.30–0.41 mm wide. The slender, cylindrical, wormlike larva is 1.1–7.0 mm long. It is white initially, turning yellowish toward the end of its growth period; the length of the head capsule of the first larval instar is 0.18–0.24 mm. The naked pupa, which is 3.4–3.7 mm long and 1.1 mm wide, is white at first and then gradually changes to yellow and eventually to brown; soon afterwards, it transforms into an adult beetle.

Similarities to other insects. For separation of the two similar species refer to *Tribolium castaneum*, which closely resembles *T. confusum*.

Physical limits and optimum rate of multiplication. The physical limits for successful development and multiplication are 20–38°C at 10–100% relative humidity. The range of optimum conditions for development are 30–33°C and 70% relative humidity. The maximum rate of increase per lunar month (28 days) is 60 times. The minimum time of 25 days for egg-to-adult development on crushed wheat occurred at 32.5°C and 70% relative humidity.

Life cycle. A female *Tribolium confusum* can be fertilized within 20 hours of adult emergence and may begin egg laying when it is 114–126 hours old. Males and females mate frequently throughout this lifetime. Generally, a female lays about 500 eggs during its life-span, which lasts from 6 months to 1 year (occasionally, 1336 days) laying eggs at the rate of 1–15 eggs per female per day. Under optimum conditions in the laboratory, an average female has been reported to produce more than 1400 eggs in a lifetime. Eggs are hatched between 3.9 and 7.7 days at 37.5–25°C and between 11.5 and 30.4 days at 22.5–17.5°C. Adults can live as long as 730–1080 days.

The larval periods, which include seven or eight instars, range from 18 to 23 days at between 35 and 27.5°C and 70% relative humidity when larvae feed on crushed wheat. The pupal period ranges from 4.9 to 7.7 days between 37.5 and 27.5°C and 70% relative humidity, and 10.3 to 21.6 days between 25 and 20°C. The egg-to-adult development periods in one laboratory study were 54 days at 24°C, 28 days at 29°C, and 26 days at 34°C. The development period, of course, varies greatly with both the food source and physical factors; food that contains the vitamin B group is essential for complete development of this species. When fed on crushed wheat, oats, and barley, *T. confusum* developed fastest on crushed oats. *T. confusum* can also complete development exclusively on seed-borne fungi. The egg-to-adult development period at 31°C and 70% relative humidity on some fungal diets was 40 days on *Nigrospora sphaerica*, 52 days on *Alternaria alternata*, and 28 days on flour and brewer's yeast (19:1, control).

Ecology. Temperature, relative humidity, nutritive value of the food, crowding, and egg cannibalism are major limiting factors in determining the rates of birth and death and the frequency of outbreak of this species. Both adult and larva feed on eggs and pupae of their own species and occasionally on those of other species. Females are more cannibalistic than males. Although it has well-developed wings, *Tribolium confusum* does not fly. It is, however, always active throughout the year and often crawls around in large numbers, infesting all available dry foods stored in protected and heated buildings. Adults can live without food for 14–18 days, occasionally up to 54 days.

Odoriferous secretions, or quinones, released from the abdominal and thoracic glands of *T. confusum* are capable of turning flour pink; they may also kill an entire population of beetles when they are kept in an airtight or nearly airtight place with little or no food. Such secretions, when absorbed in the food, also keep the beetles away. The chemical composition of quinones is the same as that produced by *T. castaneum* described earlier. *T. confusum* has a high potential for increase. It is estimated that when a male and female are placed in clean flour under favorable conditions, the pair can produce over one million individuals in 150 days.

Natural enemies. *Tribolium confusum* is attacked by several external and internal parasites. Some of its more important internal parasites are *Farinocystis tribolii* Weiser, *Egregarinina*, *Adelina tribolii*, *Nosema*, *Raillietina*, and *Hymenolepis* (the last two are tapeworms). The following mites and wasps are some of the external parasites of *T. confusum*: *Acarophenax tribolii*, *Pyemotes ventricosus* Newport, *Rhabdepyris zeae* Turner and Waterston, and *Holepyris sylvanidis* (Brethes).

Order: Coleoptera
Family: Tenebrionidae

Tribolium destructor Uyttenboogaart

Synonym: *Aphanotus* (*Tribolium*) *destructor* (Uyttenboogaart)
Common names: large flour beetle (dark flour beetle, false black flour beetle)

Economic importance. *Tribolium destructor* was first discovered on violet seeds in Erfurt, Germany, in 1933 and was described by Uyttenboogaart in 1934. Within two decades it became a pest of economic importance in milled cereals and bakery products and in packaged foods in flour mills, granaries, silos, and warehouses in Sweden and northern Europe, and to a lesser extent, Britain, Europe, USSR, western United States, and Canada. Although it is unable to thrive on sound seeds, *T. destructor* has been well documented as a minor pest of flour and feeds occurring at irregular intervals in Canadian flour mills and warehouses. It is also a minor household pest that infects milled cereal products. A change in the status of this storage pest seems to have taken place in some northern European countries, such as Denmark, where it has become more common in households than in storage premises during the past 30 years.

Geographical distribution. *Tribolium destructor* is cosmopolitan but it occurs more frequently in northern Europe than elsewhere. It has been reported from Sweden, Norway, Denmark, Netherlands, Federal Republic of Germany, Yugoslavia, USSR, France, Italy, United Kingdom, Canada, United States, Argentina, Israel, Saudi Arabia, Ethiopia, India, and People's Republic of China. In Canada, *T. destructor* has been recorded sporadically in flour mills and households since 1936, usually in the provinces of Alberta, Manitoba, Saskatchewan, Ontario, and Quebec.

Climatic adaptability. *Tribolium destructor* is adapted to a temperate climate, but it is also relatively cold-susceptible and cannot overwinter in unheated granaries (minimum temperatures -7°C and -2°C) in Sweden and England. In Sweden, an exposure to 0.5–5°C can kill all its life stages in 1 month; all developmental stages die in 40 days at 3.5°C or 10 days at -2°C; adults and larvae die in 3 days at -6°C. *T. destructor* is, however, resistant to unfavorable conditions of relative humidity and nutrition. Its adults can survive in warm and dry conditions (wheat with 10.8% moisture content) for up to 2 years. Larvae of *T. destructor* can survive for only 15 minutes at 50°C and eggs for only 5 minutes.

Food. *Tribolium destructor* feeds on cereals, oilseeds, dried fruits, potato flakes, and other stored foods.

Types of damage and symptoms. Stored products infested with *Tribolium destructor* show direct damage similar to that caused by *T. confusum*. The insect communicates a strong, unpleasant, disinfectant smell to foodstuffs, rapidly rendering them unusable. Adults produce quinone secretions, which contain 2-methyl- and 2-ethyl-1,4-benzoquinones. Beetles are spread with infested products often through contaminated, empty bags; adults and larvae are active (adults seldom fly) and move through cracks in packing materials and walls. Infestation can be detected by looking for adults and larvae in such places. Bread made of wheat flour heavily infested with *T. destructor* has poor quality and taste, specifically dark crumbs, reduced sizes of slices, and a distinct, offensive taste and odor.

Description. The adult beetle has a shiny black or very dark brown body with lighter and reddish appendages. It is 4.5–5.7 mm long and 1.4–1.8 mm wide across the elytra. Each larval instar can be distinguished by the width of the head capsule. The width (range and mean, in microns) of head capsules of seven or eight larval instars (I–VIII) are as follows: I, 195–255, 215; II, 256–308, 285; III, 308–369, 348; IV, 374–543, 450; V, 564–682, 630; VI, 692–820, 775; VII, 815–917, 855; and VIII, 897–1026, 948. The last larval instar of *Tribolium destructor* develops a "wanderlust," becoming restless and creeping around as if it is searching for something. This period often lasts for 5 days, after which pupation occurs. But if the larvae are disturbed by other larvae, wandering resumes, thereby delaying the pupal period for as long as 5 weeks.

Similarities to other insects. *Tribolium destructor* adults are similar in general appearance to *T. confusum* and *T. castaneum*, but *T. destructor* can be separated by its larger size (body not longer than 4.4 mm in other beetles) and darker to almost black color. *T. destructor* has a loose, indistinct, five- or six-segmented antennal club that gradually thickens toward the apex, and a prominent ridge above each eye on the head; the eye of *T. destructor* and *T. confusum* is 1–2 facets wide at its narrowest point, as in *Alphitobius laevigatus*.

Physical limits and optimum rate of multiplication. The complete development of *Tribolium destructor* occurs at 13–30°C and 10 to almost 100% relative humidity. The optimum condition for egg-to-adult development is between 24 and 28°C and 70 and 75% relative humidity.

Life cycle. Female beetles begin to lay eggs singly on flour or other powdery substrates, usually 1.6 eggs per female per day. Eggs are laid after a preoviposition period during which newly emerged adults feed and attain sexual maturity. This preoviposition period varies from 3–4 months at 12–16°C to 1–2 weeks at 25–30°C. Mating occurs several times during adult life, even as late as 18 months after emergence, but repeated mating is not required for normal production of fertile eggs. Unfertilized females lay eggs, but none hatch. The number of eggs laid per female for each male–female pair reared on wheat and rye flour at 70–75% relative humidity ranged from 73 to 129 at 13–15°C, 585 to 883 at 14–21°C, 400 to 1239 at 25–26°C, 236 to 526 at 28°C and 0 to 80 at 30.5–31.5°C; eggs laid in the last temperature did not hatch. The oviposition period may last up to 970 days at 14–21°C. In flour of 85% extraction, a female can lay as many as 1299 eggs; 68% of such eggs would be fertile. Maximum egg hatching, 80%, occurs at 28°C, and only 10% hatch occurs at 13.5–14°C. The egg-to-adult development period lasts for 39 days at 30.5–31.5°C and 212 days at 15–17°C. At 19–20°C the egg stage lasts for 12 days, the larval stage 70 days, and the pupal stage 17 days; the total development period is 99 days. Adults live for prolonged periods after completion of reproductive activity. In an isolated case, one pair reared on flour at 15–17°C lived for about 4 years. The egg-to-adult development period also varies with the composition of food substrates on which *Tribolium destructor* is reared. Thus, when reared on a mixture of wheat flour and bran at 24°C, *T. destructor* completes its development in 3 months; but when reared on peanuts, hazelnuts, almonds, corn, and cracked wheat, this period could be as long as 7.5 months. When fed on half kernels of wheat, the insect can complete development in 150 days or longer, but on finely ground wheat the period can be less than 150 days. The longevity of the adults ranges from 290 to 730 days and occasionally from 3 to 4 years. As a rule, high temperature reduces longevity and low temperature promotes it. There are usually two or three generations per year.

Ecology. *Tribolium destructor* spreads rapidly in houses by crawling and easily enters wardrobes, pantries, and cupboards. It can attack dead insects such as *Ephestia kuehniella*, on which it can complete development. Insulating materials in houses, such as glass wool, panels of wood fiber, and cork often provide desirable sites for pupation of wandering late-instar larvae, causing damage to the house. Infested stored products are the main source of reinfestation of *T. destructor*. Generally, this species attacks cereal or seed stocks that contain a high proportion of broken grains or whose moisture content is high. It can often survive with little or no food for prolonged periods in commodities such as furs and textiles and in sound kernels of rye, barley, and oats.

Natural enemies. The cannibal mite, *Cheyletus eruditus* (Schrank), attacks the eggs and young larvae of *Tribolium destructor* in the stored-grain habitat. *T. destructor* is sometimes associated with *Pyemotes ventricosus* (Newport). In the USSR, *T. destructor* is an intermediate host of the dwarf tapeworm *Hymenolepis nana* Siebold, a widely distributed pathogen of man, which can complete its entire cycle in a single host. Larvae of *T. destructor* can be infected by endoparasites, such as the microsporidian *Nosema whitei* Weiser and the coccidian *Adelina tribolii* Bhatia. An aphid parasite, *Entomophthora virulenta* Hall & Dunn, has also been associated with mature larvae of *T. destructor*. A gregarine, *Didymophyes minuta* (Ishii) Watson, can also be a parasite of *T. destructor* larvae.

Order: Coleoptera
Family: Tenebrionidae

Tribolium madens (Charpentier)

Synonym: *Tenebrio madens* Charpentier. According to D.G.H. Halstead, in Britain the so-called *Tribolium madens* species from North America identified before 1968 is not the true *T. madens*, which occurs exclusively in the Old World.
Common name: European black flour beetle

Economic importance. *Tribolium madens* is a secondary stored-product pest. It is common in flour mills and warehouses in some northern and eastern European countries, particularly Czechoslovakia and Yugoslavia, where the quality of cereal products is lowered by its infestation. It is often found in flour in railway boxcars in Eastern Canada and occasionally in grain in the United States. Flavor analysis of wheat bread made from flour infested with *T. madens* showed a distinctive *p*-benzoquinone aroma and flavor after the first month of infestation. *T. madens* is often a permanent inhabitant in the hives of honey bees, where it causes considerable damage to pollen stockpiles. In nature it lives under the bark of trees.

Geographical distribution. Although *Tribolium madens* is a cosmopolitan pest, it is more common in the Old World than in the New World. Countries from which properly identified insects of this species have been reported include France, Poland, Czechoslovakia, Bulgaria, Austria, Federal Republic of Germany, Hungary, Yugoslavia, Greece, USSR, Morocco, Egypt, Portugal, India, Finland (imported), United States, and Canada (in railway boxcars).

Climatic adaptability. *Tribolium madens* is a moderately cold-hardy species adapted to a temperate climate. In Yugoslavia it can overwinter in large numbers in flour mills and unheated granaries and can survive 3–6°C temperatures. *T. madens* has a narrow temperature range for development. In temperate countries the insects pass the winter months as large larvae in a resting stage (diapause).

Food. *Tribolium madens* feeds primarily on cereal products, although in its natural habitat it has been recorded from rotting wood and tree bark. It has been reported from various milling fractions of cereals in flour mills, wheat feed, and bee pollen.

Types of damage and symptoms. Infestation of cereal products by *Tribolium madens* in flour mills causes quality loss of milling stocks; infested foodstuff contains insect parts and excreta and has an off-odor. This insect is not known to attack undamaged sound cereal kernels.

Description (Fig. 35). Adult beetles are very dark brown or black, moderately shiny to dull, robust, 3.9–5.1 mm long and 1.5–1.9 mm wide, with legs and antennae dark brown to brown; the ratio between the length and width of the body is about 2.7. Larvae are dark brown, with relatively few leg setae and many irregularly distributed short setae with inconspicuous bases on abdominal segments; basal setae are much longer than apical setae. On pupal abdominal segments, there is a single long seta on each side and many short setae.

Similarities to other insects. Because of a close similarity in color and general appearance to *Tribolium audax*, *T. madens* has long been confused with that species. But the two species can be separated by their body shape, punctures between eyes, eye size and separation, pronotum, elytra (wing cover), and male genitalia. Interspecific breeding trials between *T. madens* and *T. audax* produce only a few infertile hybrids. D.G.H. Halstead has summarized these distinctive characteristics between the two species as follows.

In *T. madens*, the body dimensions of the adult are larger (3.89–5.09 mm long), less elongated, and more robust than those of *T. audax*. Punctures of the region between the eyes are not dense and are separated transversely by one to two breadths. Eye size and ventral separation are larger, separated by 1.6–2.3 times the ventral transverse diameter. The pronotum is generally more transverse and more convex, and the scutellum is broader. Male anterior femora have subbasal setiferous pits. Elytra are less elongate, with a length-to-breadth ratio of 1.7–1.8:1.0. Male genitalia have a strongly emarginate apex; the aedeagus has paramere tubes with sides sinuate, slightly bent ventrally. The periphallic sternite (sternite VIII) is with apex strongly emarginate. Tergal color is dark brown. The abdominal tergites have relatively few long setae; basal setae are much longer than apical setae. Many irregularly distributed short setae are present. Setal bases are inconspicuous; cerci are slightly less slender and less curved than those of *T. audax*. Each pupal abdominal tergite has a single long seta on each side and many short setae.

In *T. audax* body dimensions of the adult are smaller (2.84–4.47 mm long), more elongate and less robust than those of *T. madens*. Punctures of the region between the eyes are dense, frequently confluent, medial, and usually separated transversely by one breadth or less. Eye size and ventral separation are smaller, separated by 2.6–3.7 times the ventral transverse diameter. The pronotum is generally less transverse and less convex, and the scutellum is narrower. The male anterior femora are simple. Elytra are more elongate, having a length-to-breadth ratio of 1.8–1.9:1.0. Male genitalia have a periphallic sternite with apex moderately emarginate; the aedeagus has paramere tubes with sides almost straight, not bent ventrally. The periphallic sternite (sternite VIII) is weakly emarginate. Tergal color and sclerotization are extremely dark brown (darkest larva among all other *Tribolium* spp.). Abdominal tergites have an apical and basal row of long setae; setae on either side of the midline are short and appear to form pairs. Basal setae are usually longer than apical setae. A few irregularly distributed minute setae are present; setal bases are conspicuous. Cerci (urogomphi) are slightly more slender and more curved than those of *T. madens*. Pupal abdominal tergites have an apical and basal row of long setae, and pairs are about midline, as in the larva. In the basal row, the second setae on each side of the midline are slightly longer than the rest.

Physical limits and optimum rate of multiplication. The physical limits for complete development for *Tribolium madens* are 22–35°C and 10–90% relative humidity. Its lower limit for development is intermediate between that of *T. confusum* and that of *T. castaneum*. The upper temperature limit of *T. madens*, being below 37.5°C, is lower than that of the other species. The optimum conditions for egg-to-adult development are 30–35°C and 65–90% relative humidity; life cycle is completed in 25–30 days.

Life cycle. Under favorable conditions (32–35°C and 70% relative humidity), the development periods in days for the life stages are egg, 3–4; larvae, 19–22; pupa, 5–6; and egg-to-adult, 25–30 days. At every temperature from 25 to 35°C, the total development period increases as the relative humidity decreases, and at each relative humidity, except 50%, it increases as the temperature decreases. *Tribolium madens* does not reproduce parthenogenetically.

Ecology. Little is known about the ecology of *Tribolium madens* except that in Europe, it is found in nature under tree bark, in beehives, and in rotten wood and is well established as an important pest of flour mills and granaries. In Canada, *T. madens* is found in flour and grain carried in old-fashioned railway boxcars. The interiors of such boxcars are constructed with tongue and groove lumber on the ends, which allows a hidden space between the lumber and the steel ends. Because the refuse collected in the space remains undisturbed for prolonged periods, the space becomes a reservoir for breeding populations of *T. madens*, *T. audax*, *T. castaneum*, and other stored-product insects. It is possible that reinfestation of grain and contamination of boxcars occur from this source.

Natural enemies. One of the most common internal sporozoan parasites infecting *Tribolium madens* is *Farinocystis tribolii* Weiser. Infected insect cultures usually contain small numbers of adults and many dead and moribund pupae or larvae of all stages; the larvae often show dark patches in the posterior segments. This parasite can almost totally destroy a *T. madens* culture in the laboratory.

Order: Coleoptera
Family: Dermestidae

Trogoderma granarium Everts

Common name: khapra beetle

Economic importance. *Trogoderma granarium* is one of the world's most dreaded pests of whole and ground stored cereals, oilseeds, maltings, copra, and other foodstuffs. Its great economic importance lies in its capacity to cause enormous loss in stored cereals through voracious feeding and heating of grain, in its ability to withstand starvation for up to 3 years and live on food with as low as 2% moisture content, and in its relative tolerance of insecticides and many fumigants. Economic losses in destroyed cereal products range from 2 to 73%, and when the pest is left undisturbed for some time, 100% of the grain can be destroyed. *T. granarium* was first reported as a pest in India in 1894, where it was claimed to have destroyed 6 or 7% of wheat stored in godowns; its common name, khapra beetle, is derived from the Hindi word "khapra," or brick, because the beetle aestivates in the pores of bricks. By 1921, *T. granarium* became a serious pest of malt houses in Britain and Germany. During 1955–1961, the U.S. government spent $9 million to eradicate this pest from California, Texas, Arizona, and New Mexico, where *T. granarium* appeared after World War II.

Geographical distribution. *Trogoderma granarium* flourishes in unheated premises in most countries of Africa, the Middle East, and southern Asia. It occurs in specialized installations where warm habitats are available, or maintains its populations in temperate climates by reinfestation through imports from tropical and subtropical countries such as Angola, Bangladesh, Gambia, Guinea, Ivory Coast, Jamaica, Mauritania, Reunion, and Sierra Leone. *T. granarium* can thrive in several countries where it is claimed to have been eradicated, including Mexico, South Africa, Tanzania (mainland), and United States. Countries in which *T. granarium* is still considered as a major pest of wheat and other cereals include Cyprus, Iraq, Pakistan, India, and Sudan. *T. granarium* does not occur in Canada, South America, northern Europe, Australia, Micronesia, New Guinea, or Ethiopia.

Climatic adaptability. *Trogoderma granarium* is extremely cold-hardy and tolerant of both high temperature and unusually low relative humidity. Although the larva is immobilized at 8°C, it can tolerate 2–4°C for 1 year. Intermittent chilling and warming kill more larvae than unbroken exposure to cold; most larvae are able to withstand –10°C for 3 days. Despite its coldhardiness, *T. granarium* has a relatively low climatic plasticity index, 131, as compared with 190 for

Rhyzopertha dominica, with which it shares a hot and dry environment in warm countries. *T. granarium* is generally the dominant insect in hot and exceptionally dry environments—it reproduces in food at 2% moisture content, a unique feature among major storage insects—outdoing its competitors such as *Rhyzopertha dominica*, *Sitophilus granarius*, or *Tribolium castaneum*. It has been predicted, often with verification from actual infestation records, that *Trogoderma granarium* flourishes in areas of the world where a mean monthly temperature above 20°C and a mean relative humidity of over 50% occur for at least 4 months of the year.

Food. The larva of *Trogoderma granarium* feeds on wheat, barley, oats, rye, corn, rice, pulses, copra, peanuts, oil cakes, flour, bran, malt, flaxseed, alfalfa seed, tomato seed, various beans, cowpeas, sorghum, grain straw, various nut meals, alfalfa hay, nutmeats, pasta, cottonseed meal, and dried fruits. Older larvae feed on whole seed, whereas the early-instar larvae feed on broken or damaged kernels.

Type of damage and symptoms. A *Trogoderma granarium* infestation can be recognized by the presence of many larvae (the longest-lived stage) and numerous cast skins near the top 30 cm of the infested mass of stored food. A single female larva consumes 0.136–0.770 mg of food per day, which is double that of the male larva. Larvae can occasionally be found as deep as 3.6 m inside bulk grain. The larva usually feeds first on the germ portion of a cereal seed and then on the endosperm; the seed coat is eaten in an irregular manner. Intense activity of the insect causes grain heating and pollution of the food material with frass, cast skins, and excreta. Wheat infested by *T. granarium* often increases in moisture content and free fatty acids.

Description. The adult is an oval, brownish black beetle, 1.5–3.0 mm long, whose body surface and elytra are covered with fine hairs, giving the body a velvety texture. These hairs are gradually rubbed off as the beetle moves around, and the adult takes on a shiny appearance. A fringe of brown hairs covers the end of the abdomen. The female is lighter in color and larger (2–3 mm) than the male (1.5–2 mm). Color differences on the body surface of the female are not marked. In the male, however, the head, thorax, and tip of the abdomen are brownish black, and the elytra and appendages are a lighter color. The antennal bases are located in grooves. The eggs are translucent, white, narrowly cylindrical, and rounded at one end. The larva is yellowish brown (yellowish white when newly hatched) and covered with long hairs; the skin between the body segments and the underside of the body is pale yellow; a tuft of long erectile hairs forms a tail projecting behind the insect. When fully grown, the larva becomes reddish brown and is 4.5 mm long. The female pupa is about 6 mm long and mostly encased in the last-cast larval skin. The male pupa is smaller. The pupal color is a lighter brown than that of the larvae.

Similarities to other insects. *Trogoderma granarium* cannot be confused with other stored-product insects, except other species of *Trogoderma* and some other dermestid beetles. Positive identification of *T. granarium* larvae requires a specialist's knowledge in taxonomy.

Physical limits and optimum rate of multiplication. The physical limits of successful development and multiplication are 24–41°C at a minimum relative humidity of 1%; occasionally, development occurs even at 15°C. The range of optimum temperature is between 30 and 37°C. Its maximum rate of increase per lunar month in 12.5 times.

Life cycle. The female lays up to 126 loose eggs singly during its 10–19 day lifetime. The egg hatches in 3–26 days to young larvae that feed on damaged seeds. Under adverse conditions, the larva can undergo facultative diapause—a condition of suspended animation that may or may not occur—and live without food for several months to 6 years. The larval stage of nondiapausing larvae normally lasts for 26–87 days and the pupal stage, 2–23 days; pupation occurs near the top surface of the infested material. The period from egg to adult varies between 25–29 days at 34–35°C and up to 310 days at 21°C; this period could be prolonged to several years in the case of diapausing larvae. The adults do not fly and live for 3–19 days, depending on the season. In India, *Trogoderma granarium* passes through four or five generations per year.

Ecology. *Trogoderma granarium* adults do not attack crops growing in the field. Infestation is usually spread in nature by actively crawling larvae, which adhere to sacks and other objects with their barbed hairs. The larvae are spread by birds and other insects, by wind, and most importantly, by humans. Larvae hidden in cracks and fissures, infested trucks, railway boxcars and shipholds may serve as a reservoir for future infestation by *T. granarium*. The larva in diapause has a remarkable power of survival under conditions of food shortage, accumulation of excrement in the food, or drops in temperature. During diapause, the larva crawls into cracks in the store and remains inactive. In a competitive situation, *T. granarium* can suppress *Sitophilus oryzae* only when the temperature is high (32–44°C) and the grain moisture content is low (9.51–15.5%). The dominance pattern is reversed when the temperature is lower (28–34°C) and the moisture content higher (11.5–16%). Relatively dry areas with very high temperatures are most suitable for the spread and multiplication of *T. granarium*. High insect population densities enable *T. granarium* to produce metabolic heat and maintain its optimum temperature in large grain masses (up to 2500 t), practically independent of ambient temperature throughout the year. The superoptimum temperatures (40–42°C) thus created near the top of bulk grain allow higher population densities along the surface layers.

Natural enemies. The eggs of *Trogoderma granarium* are consumed by the straw itch mite, *Pyemotes tritici* (Lagrèze-Fossat & Montané) (Newport). A bethylid parasite, *Choetospila elegans* Westwood, a cheyletid mite, *Acaropsis* sp., and certain species of spiders also attack larval stages of *T. granarium*.

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Appendix I

Latin and common names of arthropod pests in flour mills, grain elevators, and feed mills in Canada (1969–1981)

Latin name	Common name	Order: Family
Acarina	mites	Acarina
Ahasverus advena (Waltl)	foreign grain beetle	Coleoptera: Cucujidae
Aleochara bimaculata (Grvh.)	a rove beetle	Coleoptera: Staphylinidae
Alphitobius diaperinus (Panzer)	lesser mealworm	Coleoptera: Tenebrionidae
Anthicus floralis (Linnaeus)	narrownecked grain beetle	Coleoptera: Anthicidae
Anthrenus scrophulariae (Linnaeus)	carpet beetle	Coleoptera: Dermestidae
Anthrenus verbasci (Linnaeus)	varied carpet beetle	Coleoptera: Dermestidae
Aphomis gularis (Zeller)	stored nut moth	Lepidoptera: Pyralidae
Attagenus pellio (Linnaeus)	a beetle	Coleoptera: Dermestidae
Attagenus unicolor (Brahm)	black carpet beetle	Coleoptera: Dermestidae
Attagenus spp.	carpet beetles	Coleoptera: Dermestidae
Carcinops quatuordecimstriata (Stephens)	a carpet beetle	Coleoptera: Histeridae
Cartodere filiformis (Gyllenhal)	a fungus beetle	Coleoptera: Lathridiidae
Cathartus quadricollis (Guérin-Méneville)	squarenecked grain beetle	Coleoptera: Cucujidae
Cryptolestes ferrugineus (Stephens)	rusty grain beetle	Coleoptera: Cucujidae
Cryptolestes pusillus (Schönherr)	flat grain beetle	Coleoptera: Cucujidae
Cryptolestes turcicus (Grouvelle)	flour mill beetle	Coleoptera: Cucujidae
Cryptolestes spp.	flat grain beetles	Coleoptera: Cucujidae
Cryptophagus cellaris (Scopoli)	a fungus beetle	Coleoptera: Cryptophagidae
Cryptophagus spp.	fungus beetles	Coleoptera: Cryptophagidae
Cynaeus angustus (LeConte)	larger black flour beetle	Coleoptera: Tenebrionidae
Dermestes lardarius (Linnaeus)	larder beetle	Coleoptera: Dermestidae
Dermestidae	dermestid beetles	Coleoptera: Dermestidae
Diptera	flies and maggots	Diptera
Endrosis sarcitrella (Linnaeus)	whiteshouldered house moth	Lepidoptera: Oecophoridae
Ephestia cautella (Walker)	almond moth	Lepidoptera: Pyralidae
Ephestia elutella (Hübner)	tobacco moth	Lepidoptera: Pyralidae
Ephestia kuehniella (Zeller)	Mediterranean flour moth	Lepidoptera: Pyralidae
Formicidae	ants	Hymenoptera: Formicidae
Gibbium psylloides (Czenpinski)	shiny spider beetle	Coleoptera: Ptinidae
Glischrochilus quadrisignatus (Say)	four-spotted sap beetle	Coleoptera: Nitidulidae
Gnatocerus cornutus (Fabricius)	broadhorned flour beetle	Coleoptera: Tenebrionidae
Haplotinea ditella	a clothes moth	Lepidoptera: Tineidae
Hexarthrum (Rhyncalus) ulkei (Horn)	a snout beetle	Coleoptera: Curculionidae
Hofmannophila pseudospretella (Stainton)	brown house moth	Lepidoptera: Oecophoridae
Isopoda	sowbugs	Isopoda: Asellidae
Larca granulata (Banks)	a pseudoscorpion	Chelonethida: Garypidae
Lasioderma serricorne (Fabricius)	cigarette beetle	Coleoptera: Anobiidae
Latheticus oryzae (Waterhouse)	longheaded flour beetle	Coleoptera: Tenebrionidae
Lathridius minutus Linnaeus (= *Enicmus minutus* (L.))	squarenosed fungus beetle	Coleoptera: Lathridiidae
Lathridius spp.	fungus beetles	Coleoptera: Lathridiidae
Lepidoptera spp.	moths and caterpillars	Lepidoptera
Lepisma saccharina Linnaeus	a silverfish	Thysanura: Lepismatidae

Appendix I

Latin and common names of arthropod pests in flour mills, grain elevators, and feed mills in Canada (1969–1981) *(continued)*

Latin name	Common name	Order: Family
Leptocoris trivittatus (Say)	boxelder bug	Heteroptera: Rhopalidae
Mezium americanum (Laporte)	American spider beetle	Coleoptera: Ptinidae
Microgramme filum (Aube)	a fungus beetle	Coleoptera: Lathridiidae
Microgramme spp.	fungus beetles	Coleoptera: Lathridiidae
Nemapogon granella (Linnaeus)	European grain moth	Lepidoptera: Tineidae
Niptus hololeucus (Faldermann)	golden spider beetle	Coleoptera: Ptinidae
Niptus unicolor (Piller & Mitterpacher)	a spider beetle	Coleoptera: Ptinidae
Obisium ischonoceles		
Orthoptera	grasshoppers	Orthoptera: Acrididae
Oryzaephilus mercator (Fauvel)	merchant grain beetle	Coleoptera: Cucujidae
Oryzaephilus surinamensis (Linnaeus)	sawtoothed grain beetle	Coleoptera: Cucujidae
Palorus ratzeburgi (Wissmann)	smalleyed flour beetle	Coleoptera: Tenebrionidae
Plodia interpunctella (Hübner)	Indianmeal moth	Lepidoptera: Pyralidae
Porcellio laevis Latreille	a sowbug	Isopoda: Porcellionidae
Pselaphochernes sp.	a pseudoscorpion	Chelonethida: (Myrmecophile)
Pselaphochernes parvus Hoff.	a pseudoscorpion	Chelonethida: Chernetidae
Psocoptera	book lice	Psocoptera
Ptinus clavipes (Panzer)	brown spider beetle	Coleoptera: Ptinidae
Ptinus fur (Linnaeus)	whitemarked spider beetle	Coleoptera: Ptinidae
Ptinus hirtellus (Sturm) (= *P. clavipes* Panzer)	brown spider beetle	Coleoptera: Ptinidae
Ptinus ocellus (Brown)	Australian spider beetle	Coleoptera: Ptinidae
Ptinus raptor (Sturm)	Canadian spider beetle (eastern)	Coleoptera: Ptinidae
Ptinus tectus (Boieldieu)	a spider beetle	Coleoptera: Ptinidae
Ptinus villiger (Reitter)	hairy spider beetle	Coleoptera: Ptinidae
Ptinus spp.	spider beetles	Coleoptera: Ptinidae
Pyralis farinalis (Linnaeus)	meal moth	Lepidoptera: Pyralidae
Rhyzopertha dominica (Fabricius)	lesser grain borer	Coleoptera: Bostrichidae
Scenopinus fenestralis (Linnaeus)	window fly	Diptera: Scenopinidae
Sitophilus granarius (Linnaeus)	granary weevil	Coleoptera: Curculionidae
Sitophilus oryzae (Linnaeus)	rice weevil	Coleoptera: Curculionidae
Sitophilus spp.	grain weevils	Coleoptera: Curculionidae
Sitotroga cerealella (Olivier)	Angoumois grain moth	Lepidoptera: Gelechiidae
Staphylinidae spp.	rove beetles	Coleoptera: Staphylinidae
Stegobium paniceum (Linnaeus)	drugstore beetle	Coleoptera: Anobiidae
Tenebrio molitor (Linnaeus)	yellow mealworm	Coleoptera: Tenebrionidae
Tenebrio obscurus (Fabricius)	dark mealworm	Coleoptera: Tenebrionidae
Tenebroides mauritanicus (Linnaeus)	cadelle	Coleoptera: Trogositidae
Thes bergrothi (Reitter)	a fungus beetle	Coleoptera: Lathridiidae
Tinea pallescentella (Stainton)	large pale clothes moth	Lepidoptera: Tineidae
Tinea pellionella (Linnaeus)	casemaking clothes moth	Lepidoptera: Tineidae
Tineola bisselliella (Hummel)	webbing clothes moth	Lepidoptera: Tineidae
Tribolium audax (Halstead)	black flour beetle	Coleoptera: Tenebrionidae
Tribolium castaneum (Herbst)	red flour beetle	Coleoptera: Tenebrionidae
Tribolium confusum Jacquelin du Val	confused flour beetle	Coleoptera: Tenebrionidae

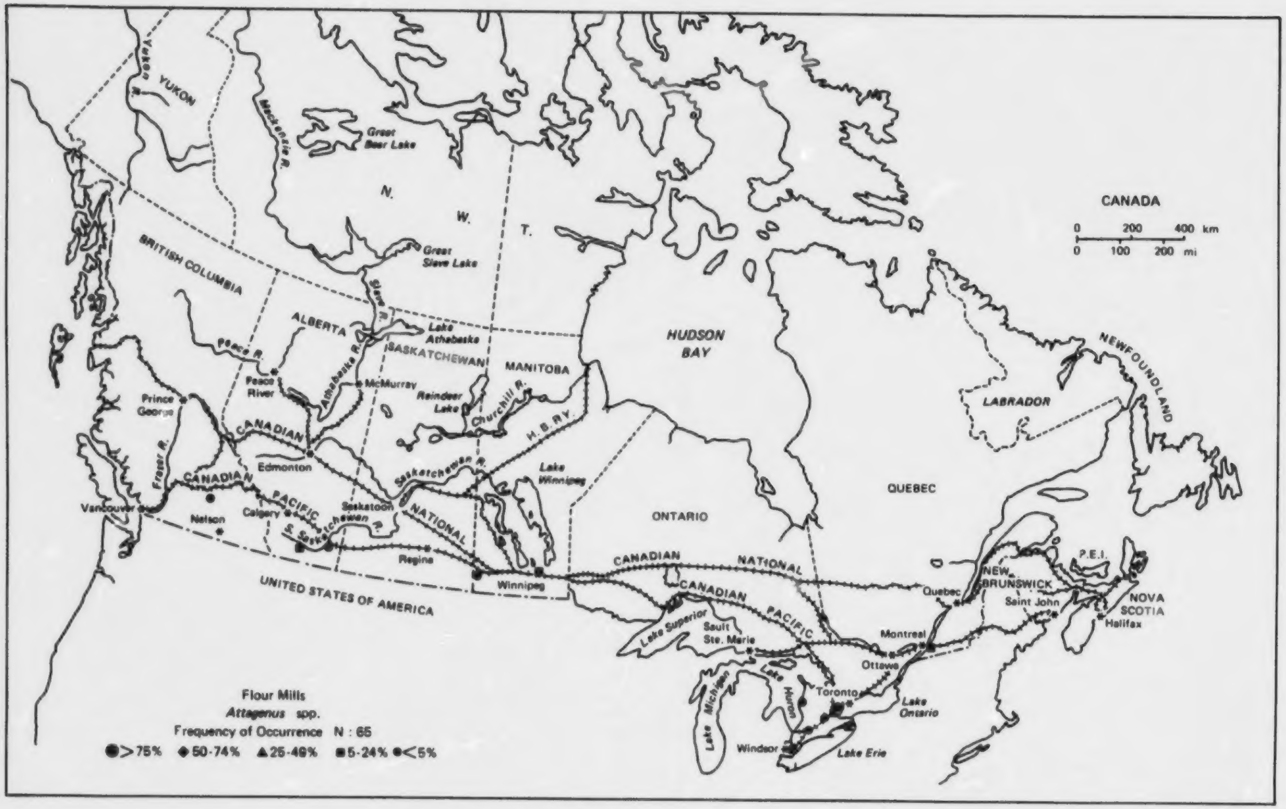
Appendix I

Latin and common names of arthropod pests in flour mills, grain elevators, and feed mills in Canada (1969–1981) *(concluded)*

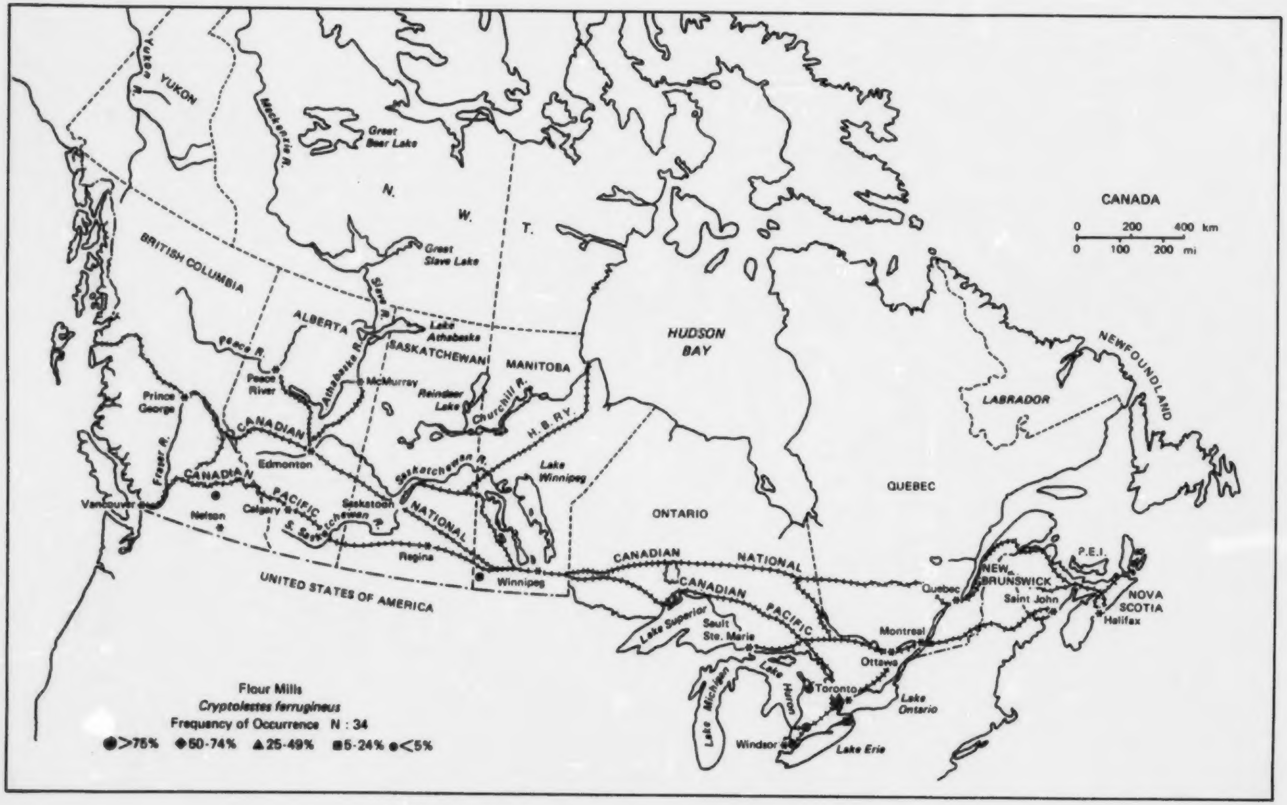
Latin name	Common name	Order: Family
Tribolium destructor Uyttenboogaart	a black flour beetle	Coleoptera: Tenebrionidae
Tribolium spp.	flour beetles	Coleoptera: Tenebrionidae
Trichoptera	caddis flies	Trichoptera
Trogium pulsatorium (Linnaeus)	large pale trogiid	Psocoptera: Trogiidae
Trogoderma inclusum (Lec.)	larger cabinet beetle	Coleoptera:Dermestidae
Trogoderma variabile (Ballion)	a carpet beetle	Coleoptera: Dermestidae
Trogoderma spp.	dermestids	Coleoptera: Dermestidae
Typhaea stercorea (Linnaeus)	hairy fungus beetle	Coleoptera: Mycetophagidae

Appendix II

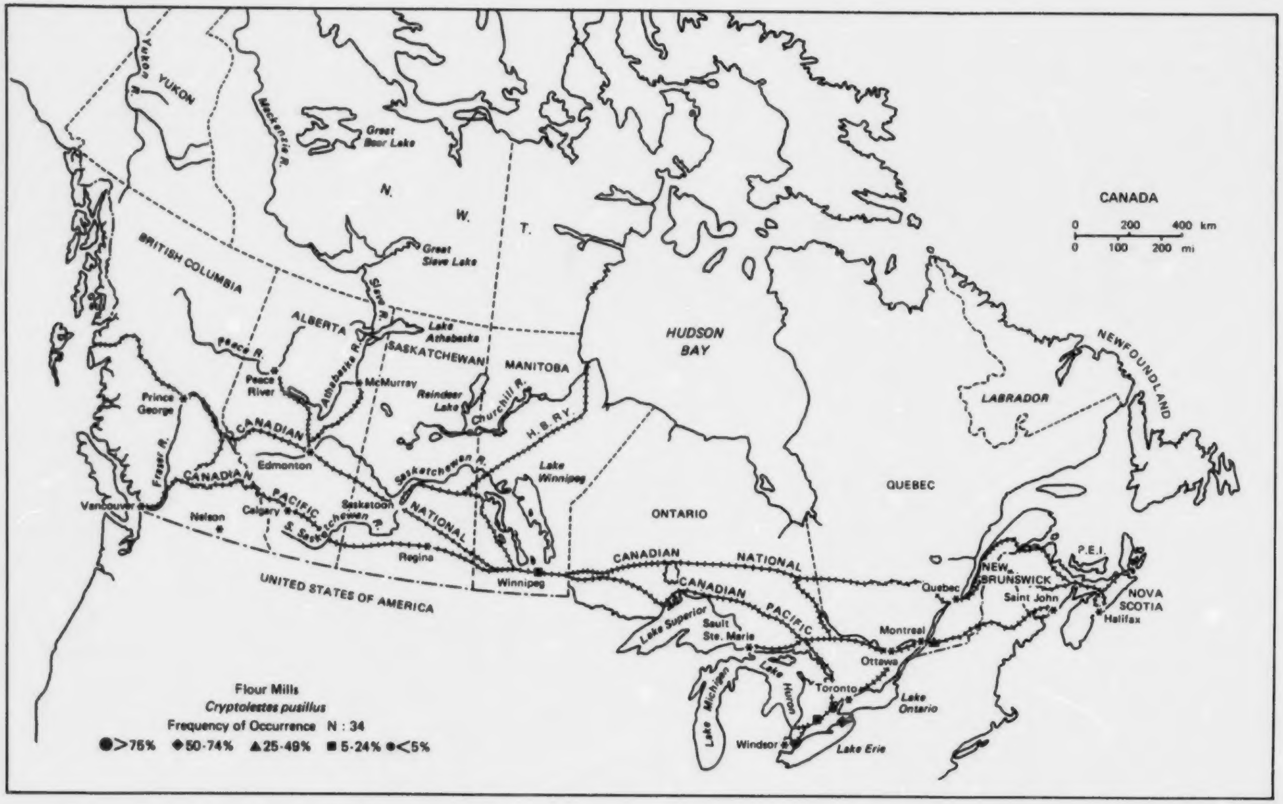
Distribution maps



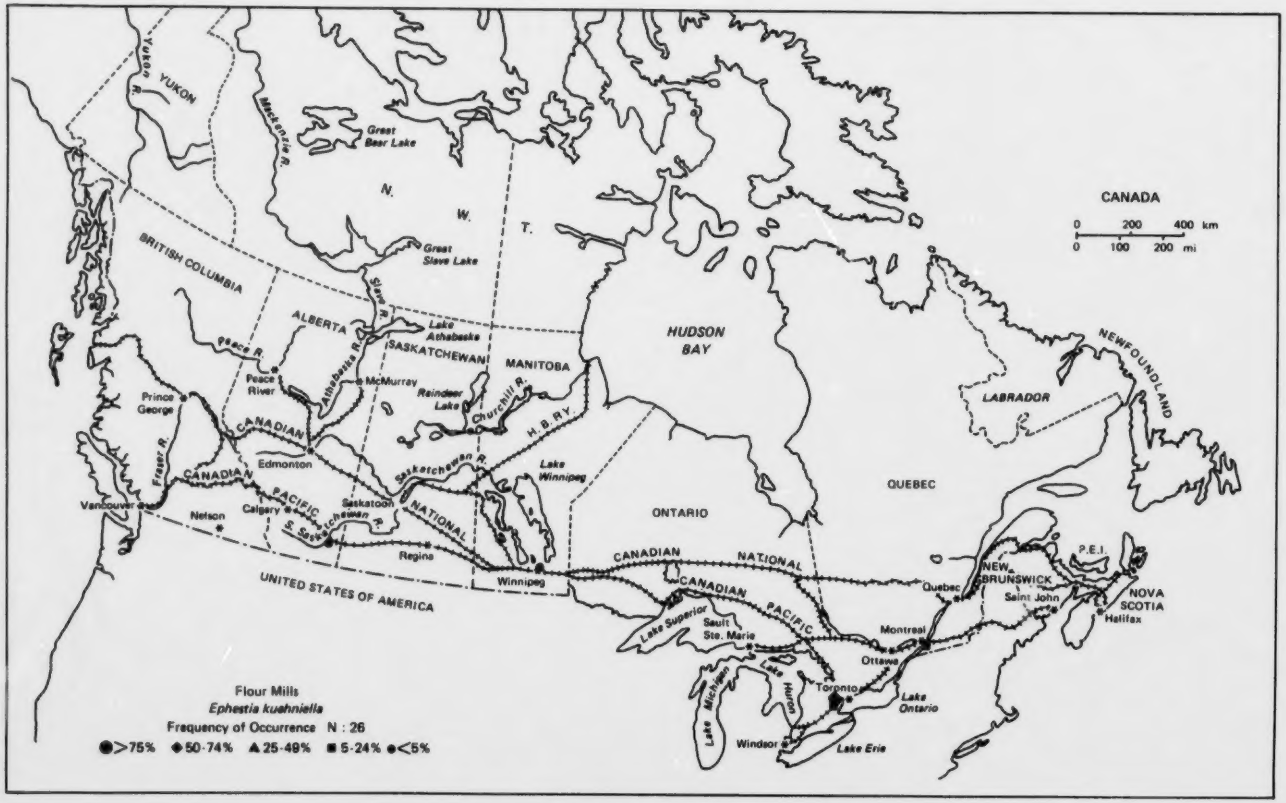
Map 1. Distribution of *Attagenus* spp. in flour mills.



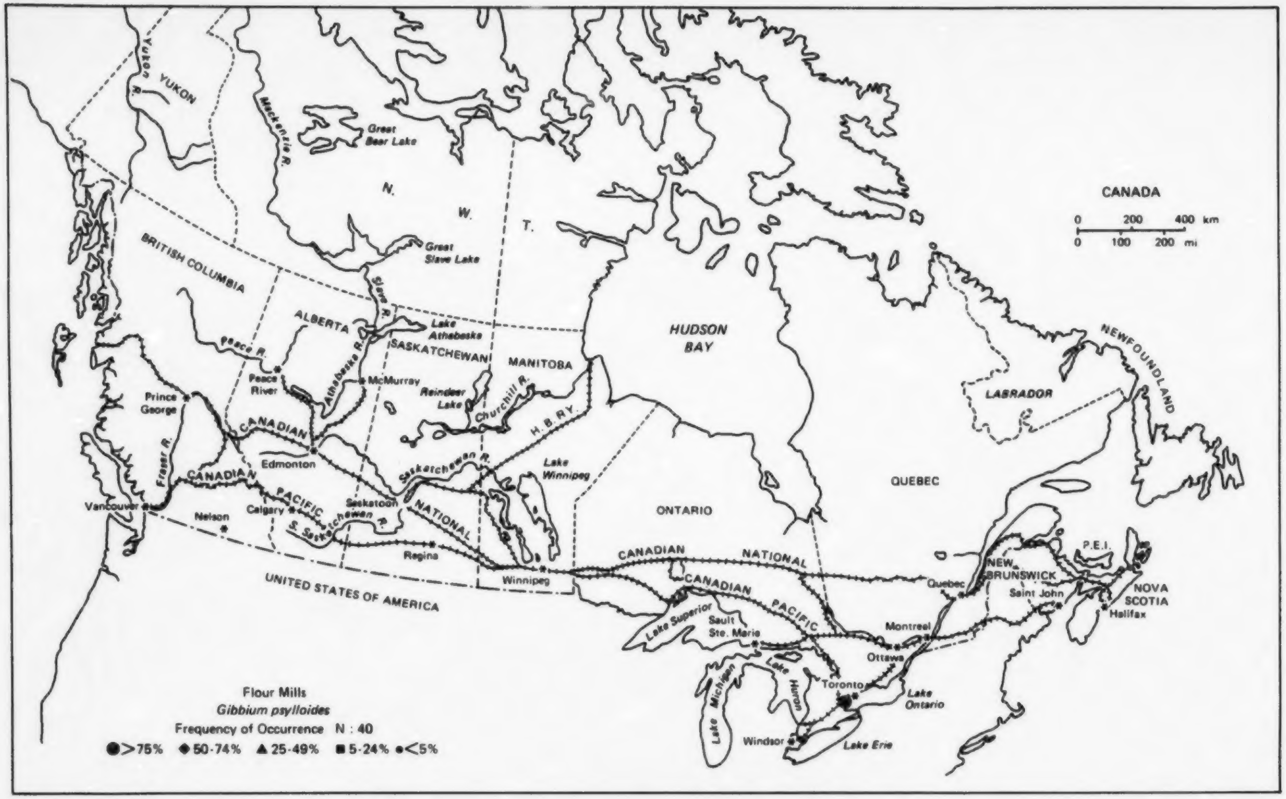
Map 2. Distribution of *Cryptolestes ferrugineus* in flour mills.



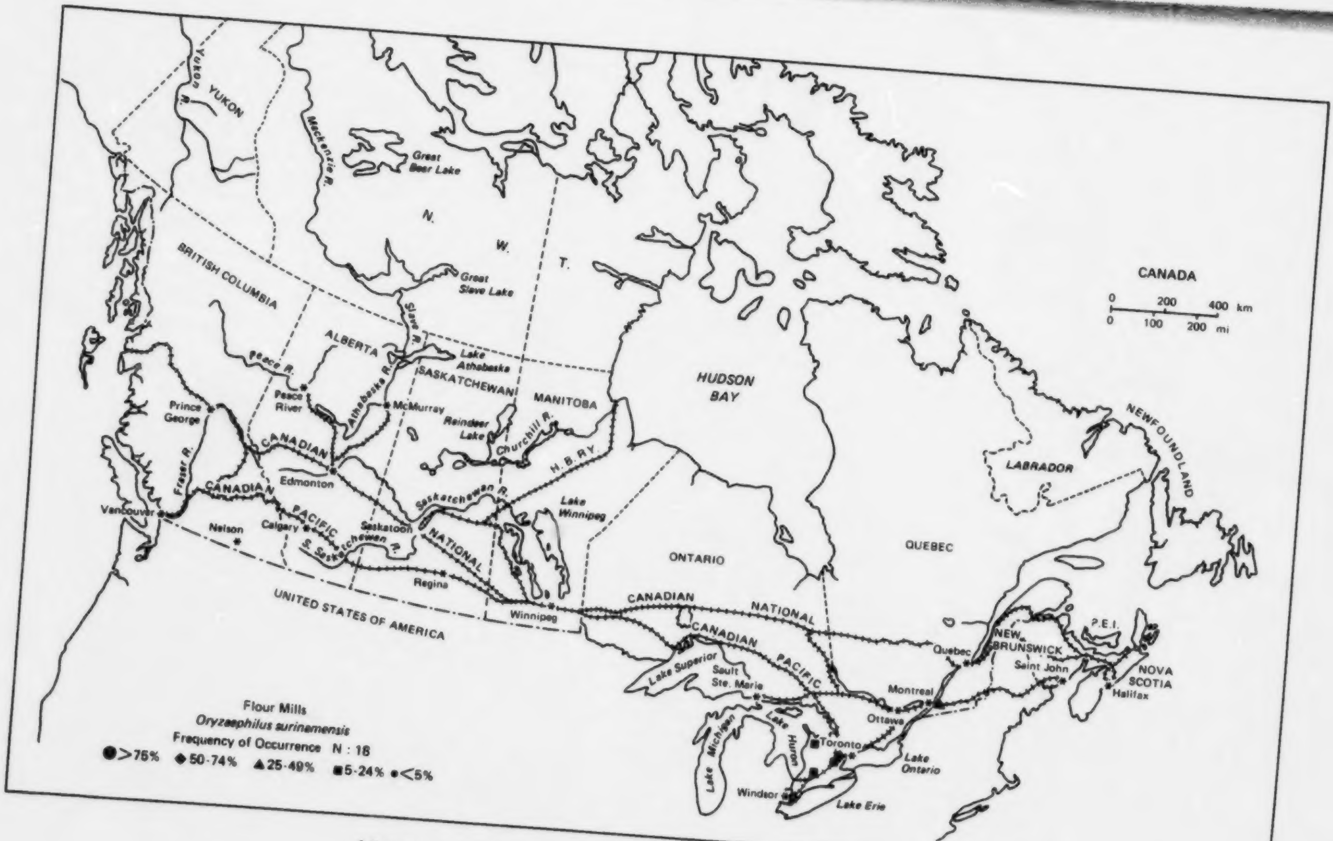
Map 3. Distribution of *Cryptolestes pusillus* in flour mills.



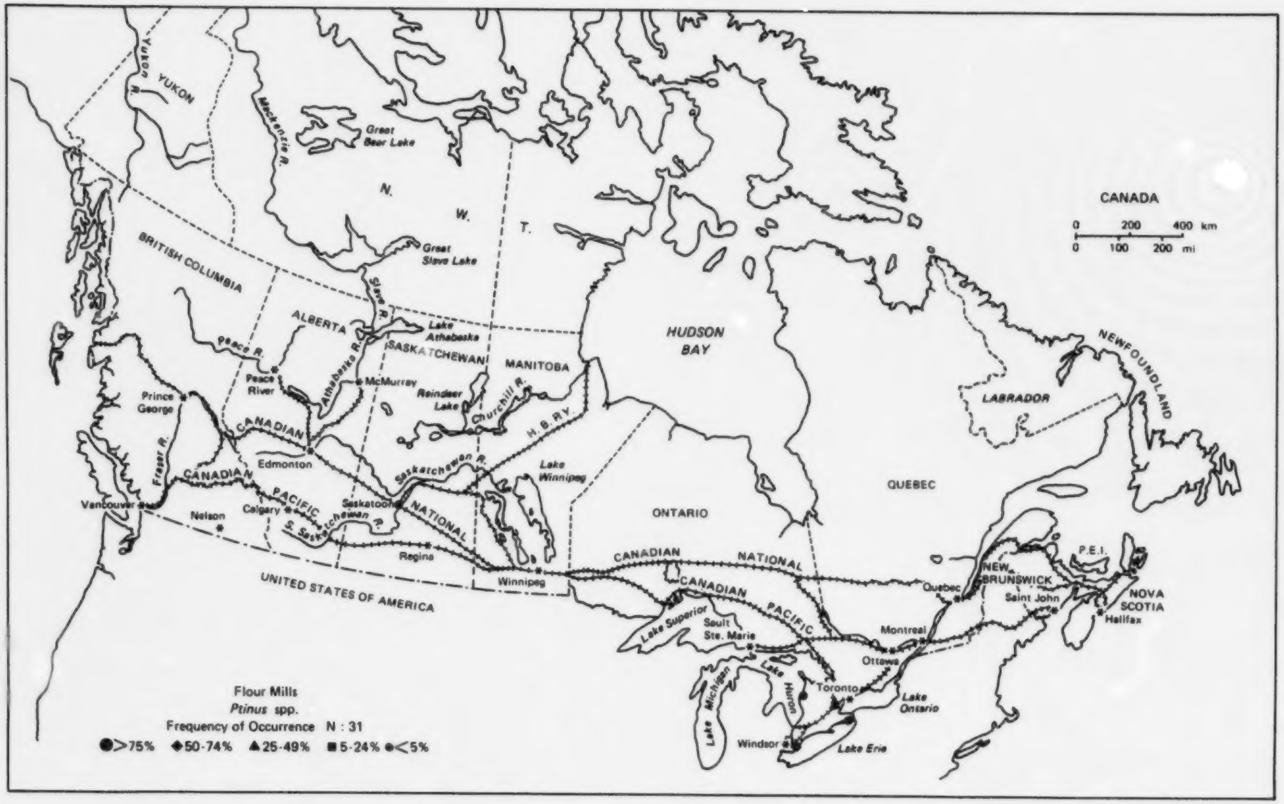
Map 4. Distribution of *Ephestia kuehniella* in flour mills.



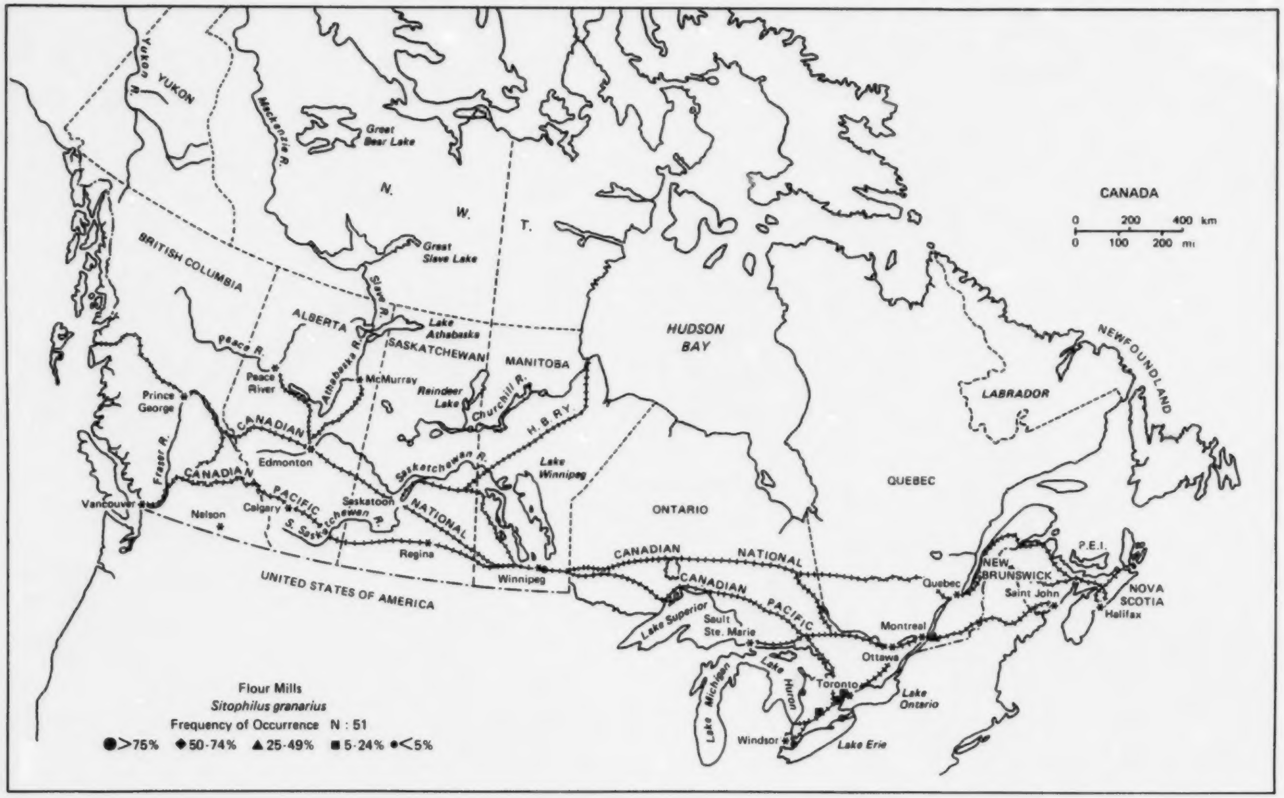
Map 5. Distribution of *Gibbium psylloides* in flour mills.



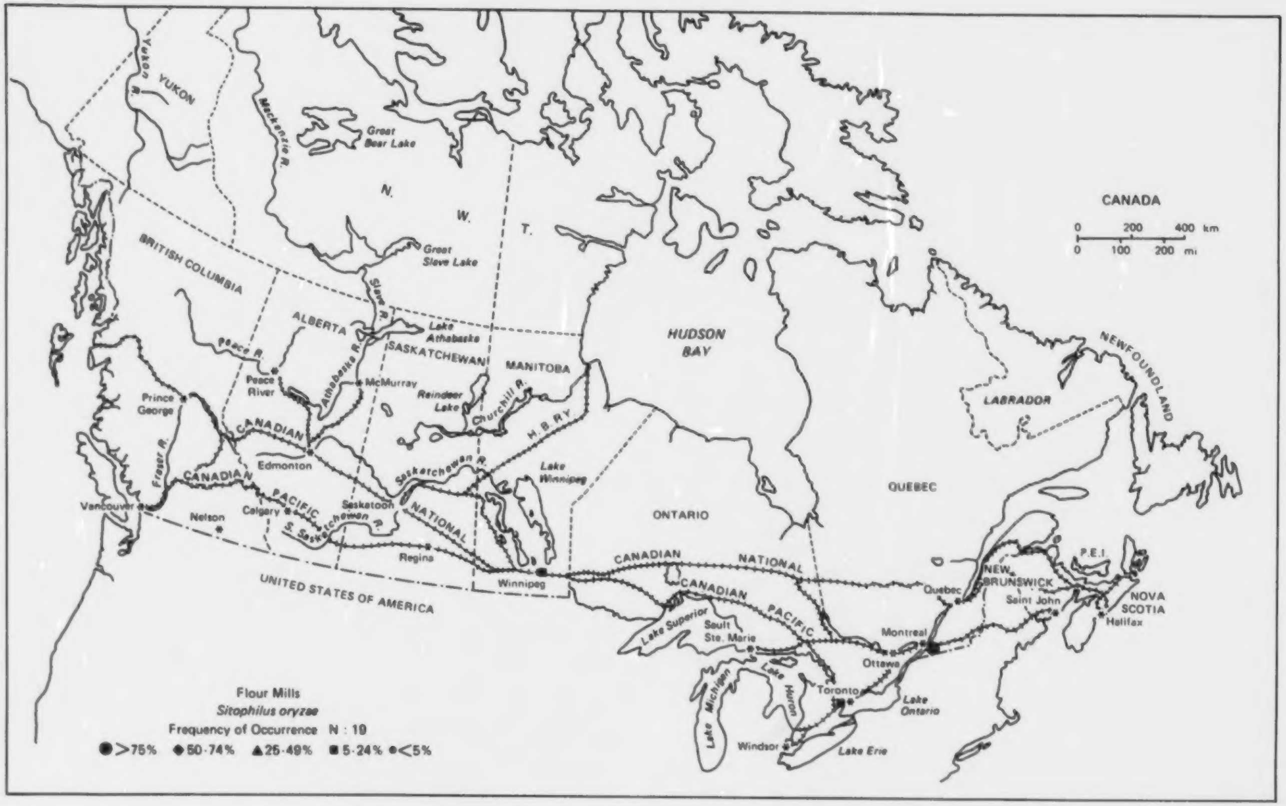
Map 6. Distribution of *Oryzaephilus surinamensis* in flour mills.



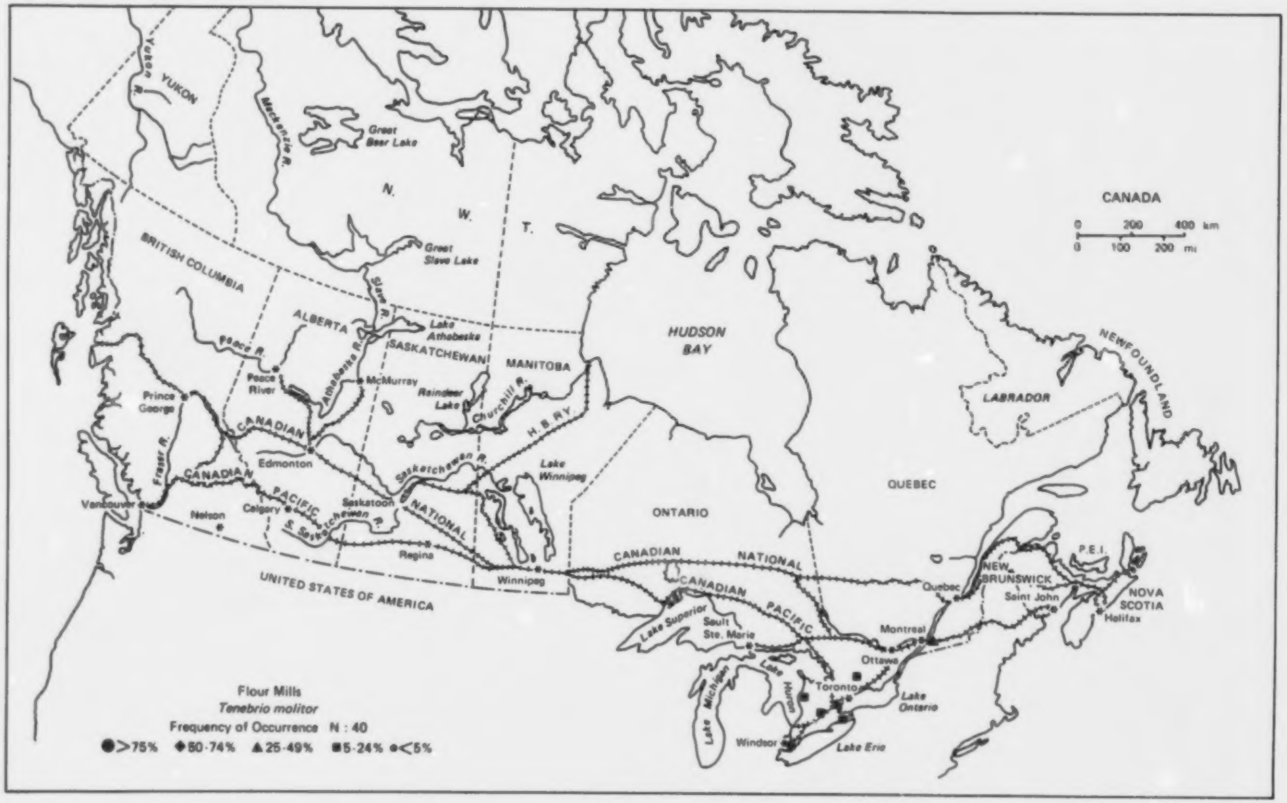
Map 7. Distribution of *Ptinus* spp. in flour mills.



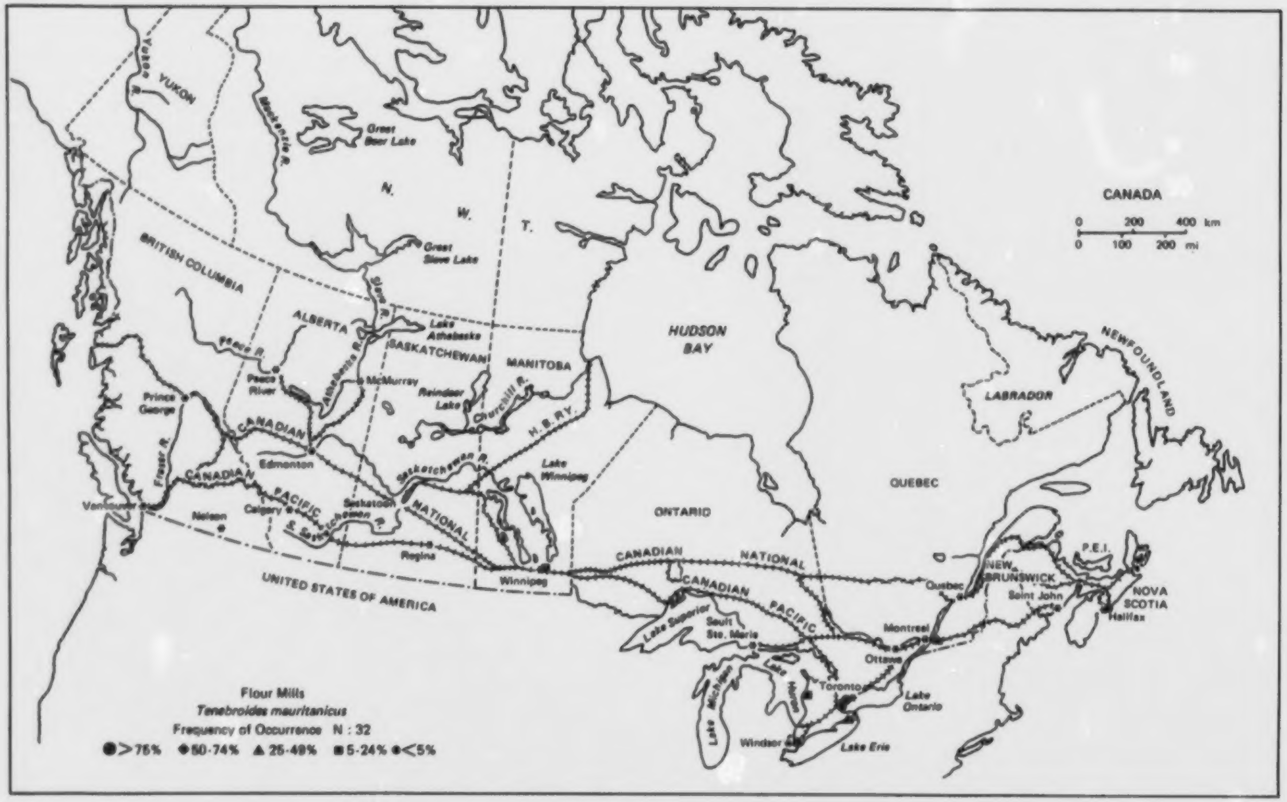
Map 8. Distribution of *Sitophilus granarius* in flour mills.



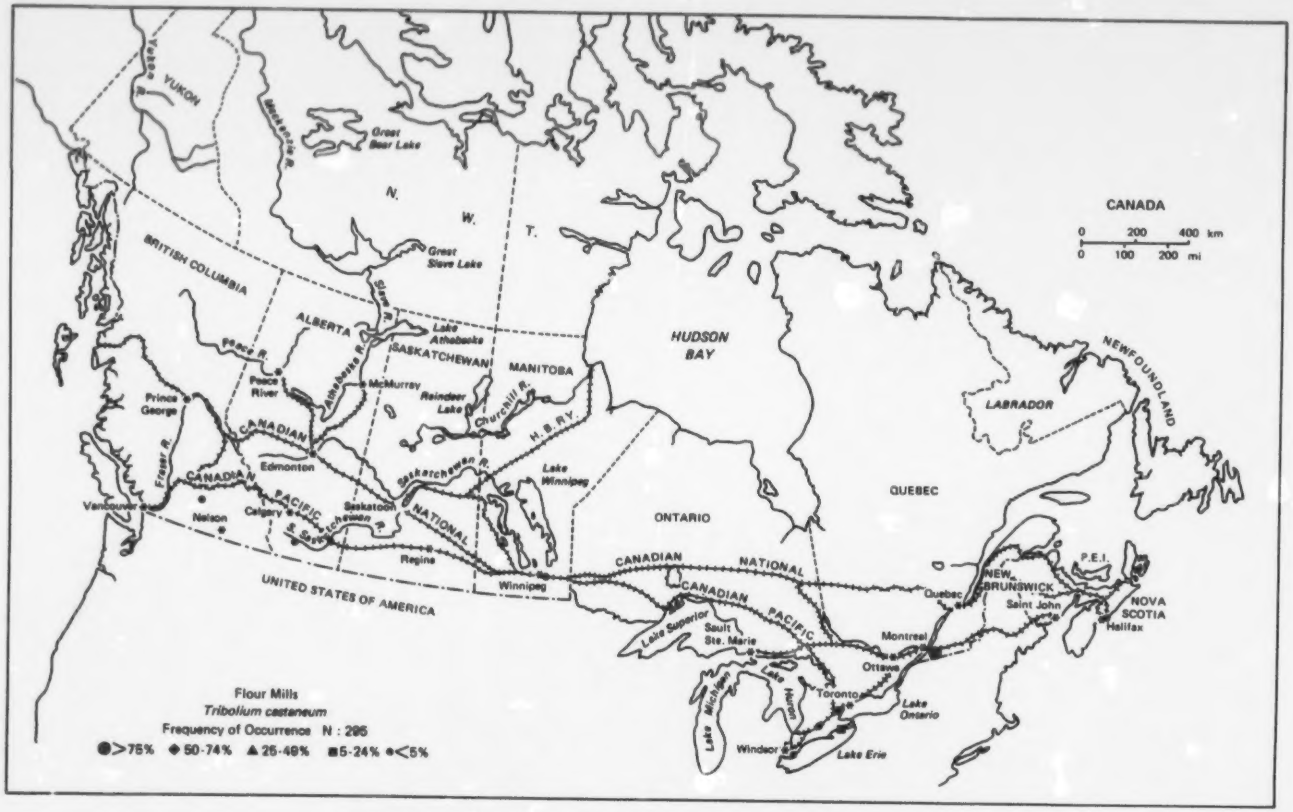
Map 9. Distribution of *Sitophilus oryzae* in flour mills.



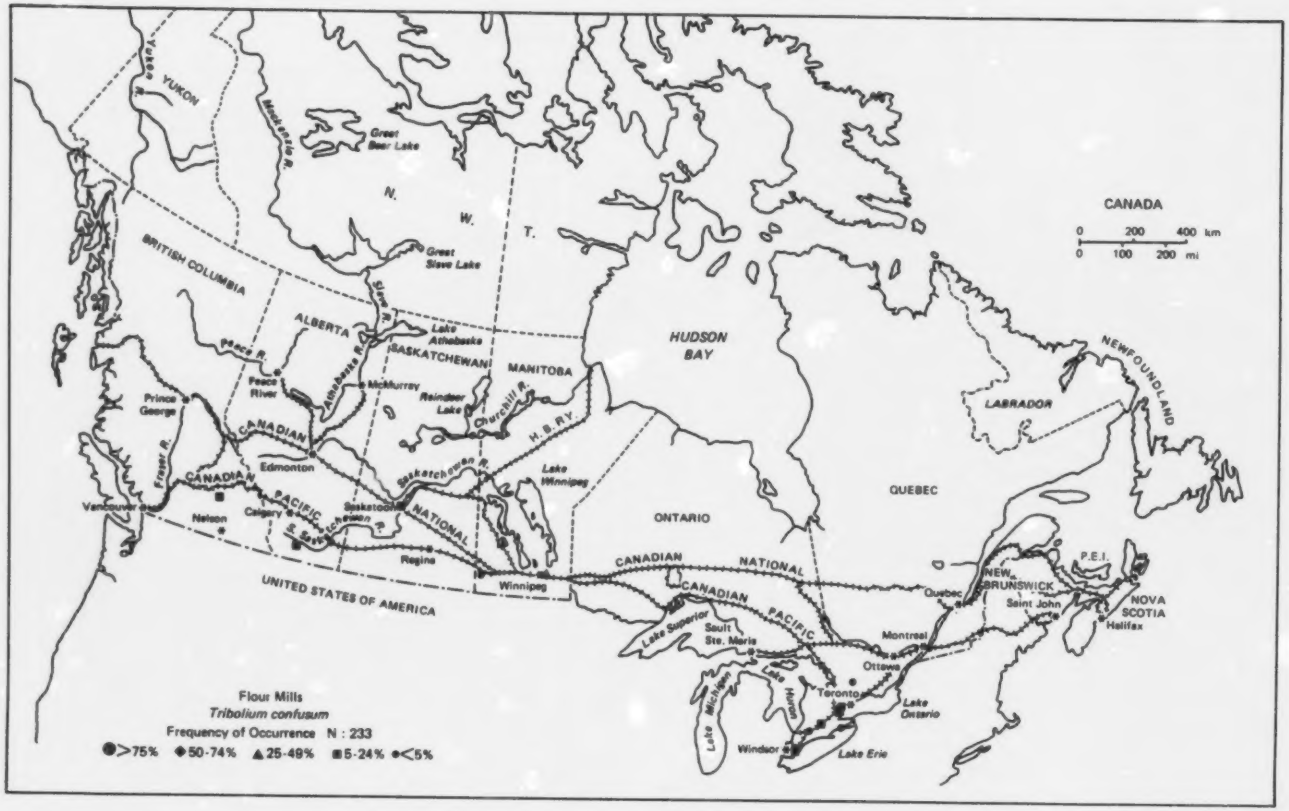
Map 10. Distribution of *Tenebrio molitor* in flour mills.



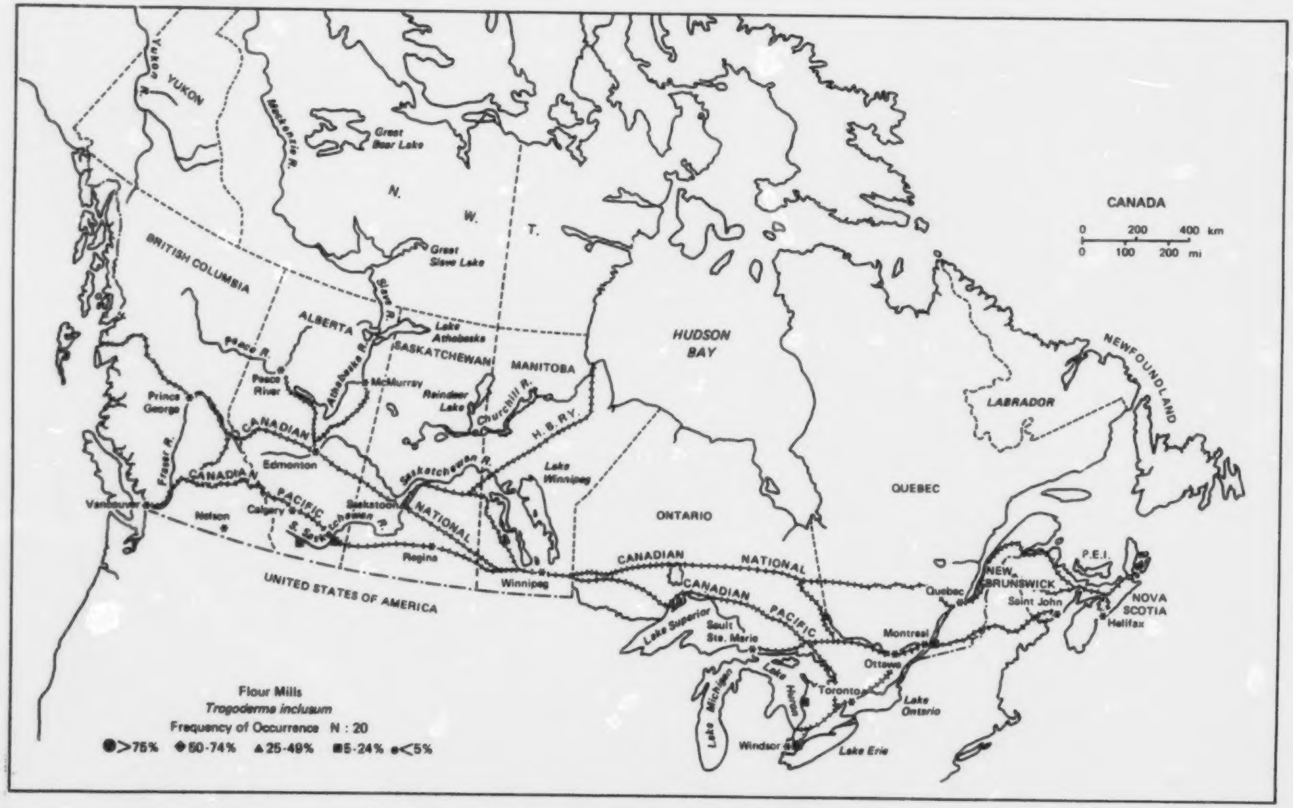
Map 11. Distribution of *Tenebroides mauritanicus* in flour mills.



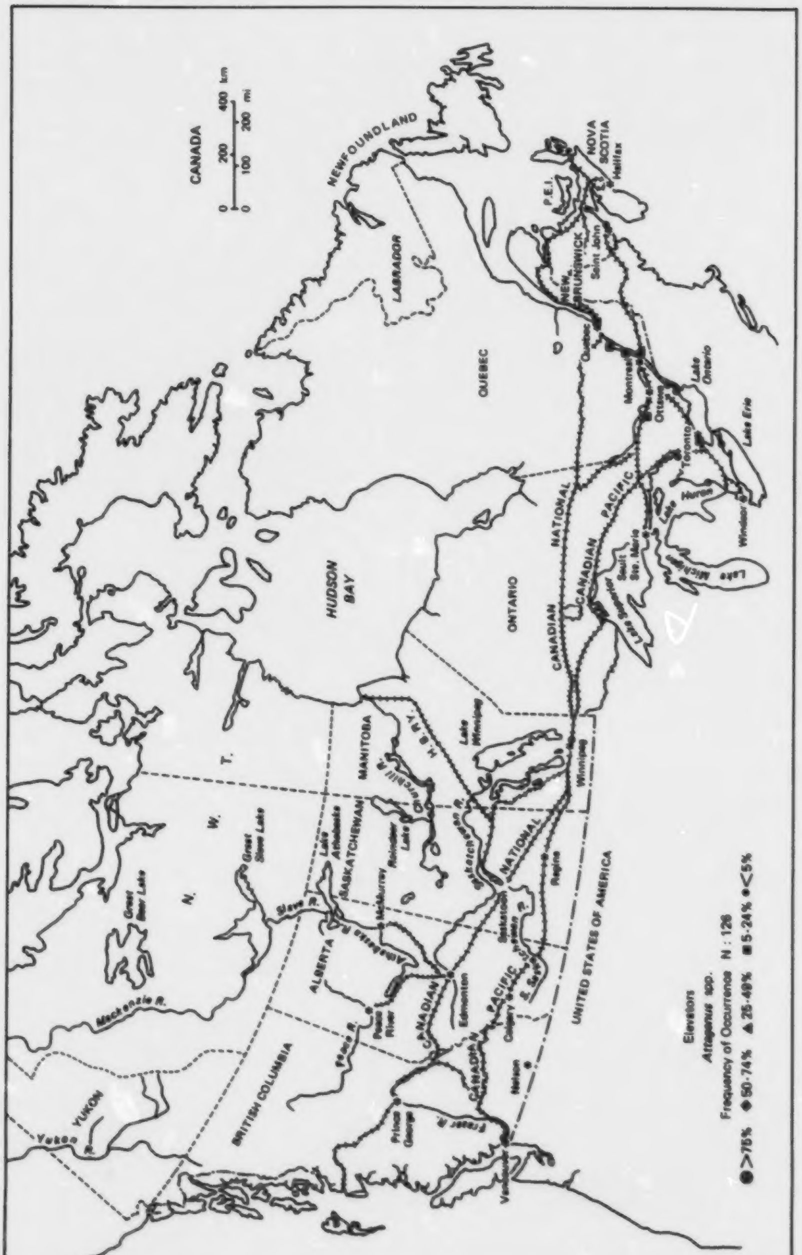
Map 12. Distribution of *Tribolium castaneum* in flour mills.



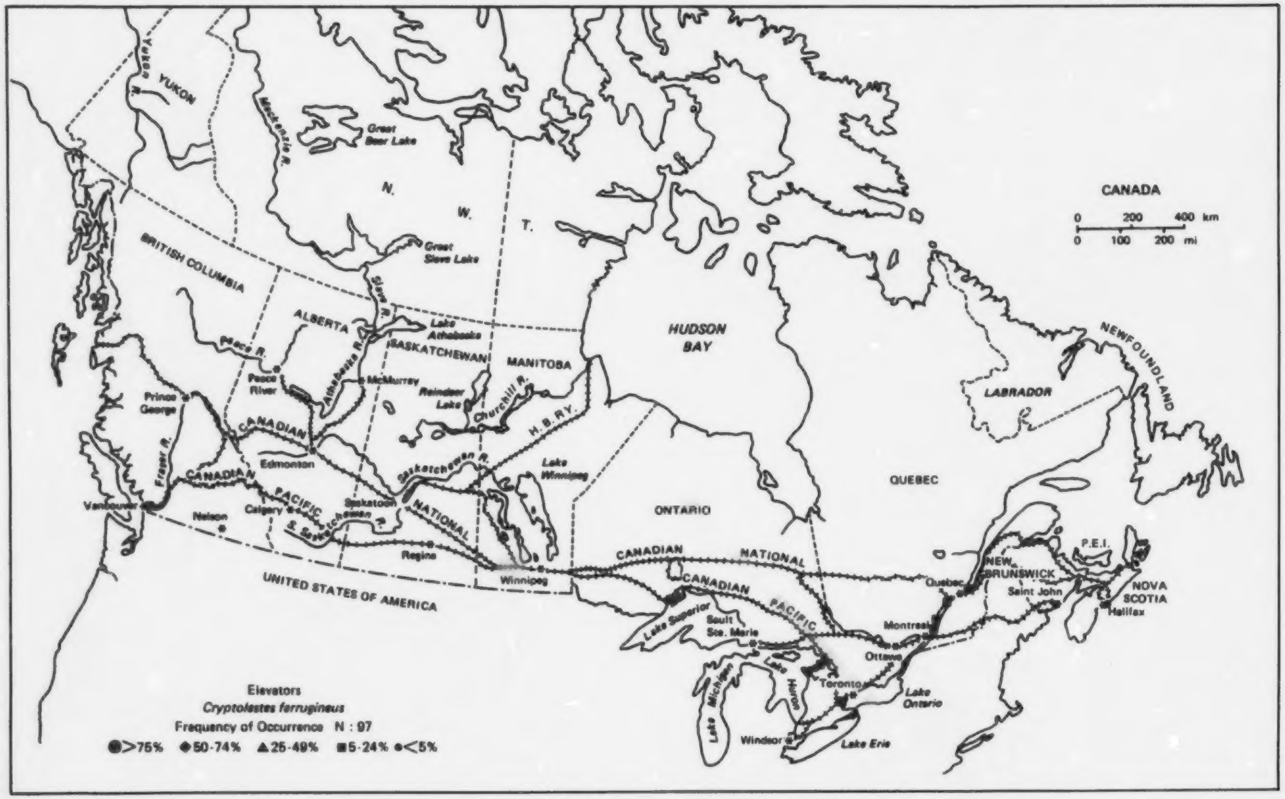
Map 13. Distribution of *Tribolium confusum* in flour mills.



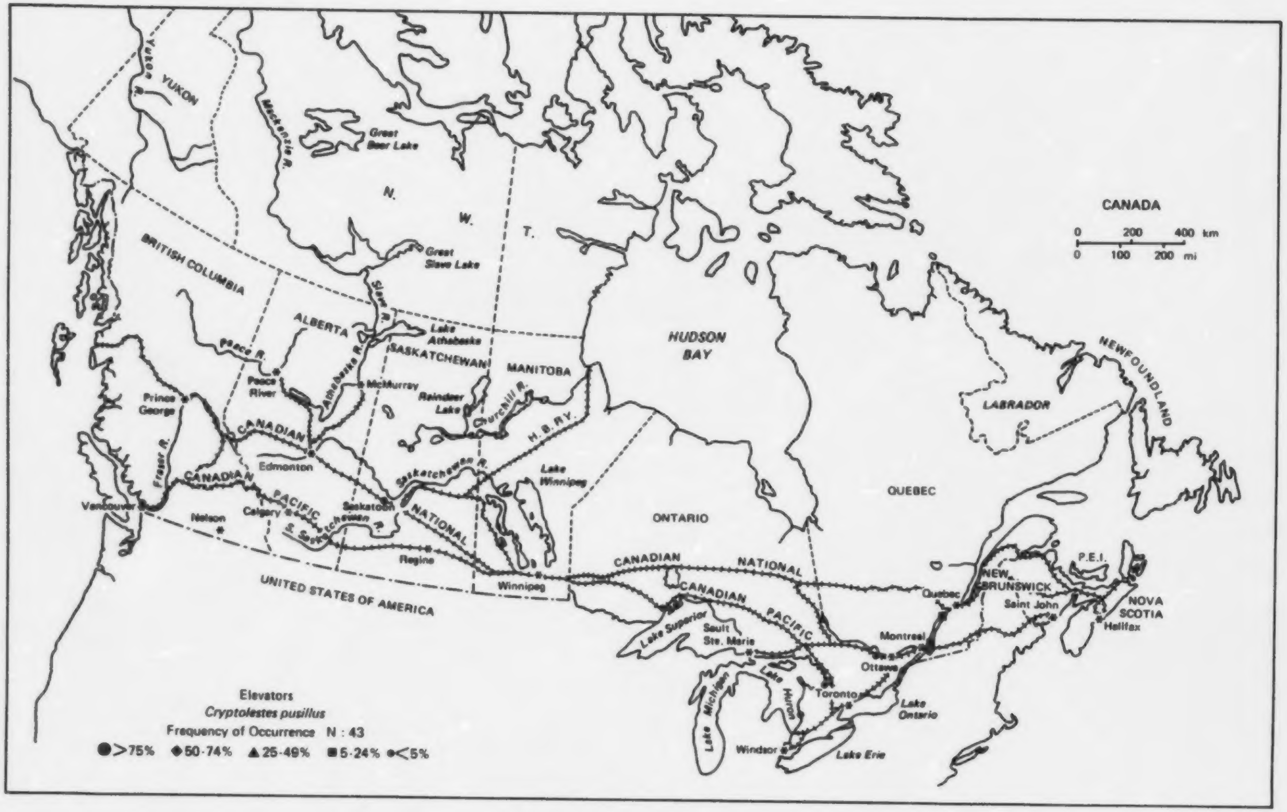
Map 14. Distribution of *Trogoderma inclusum* in flour mills.



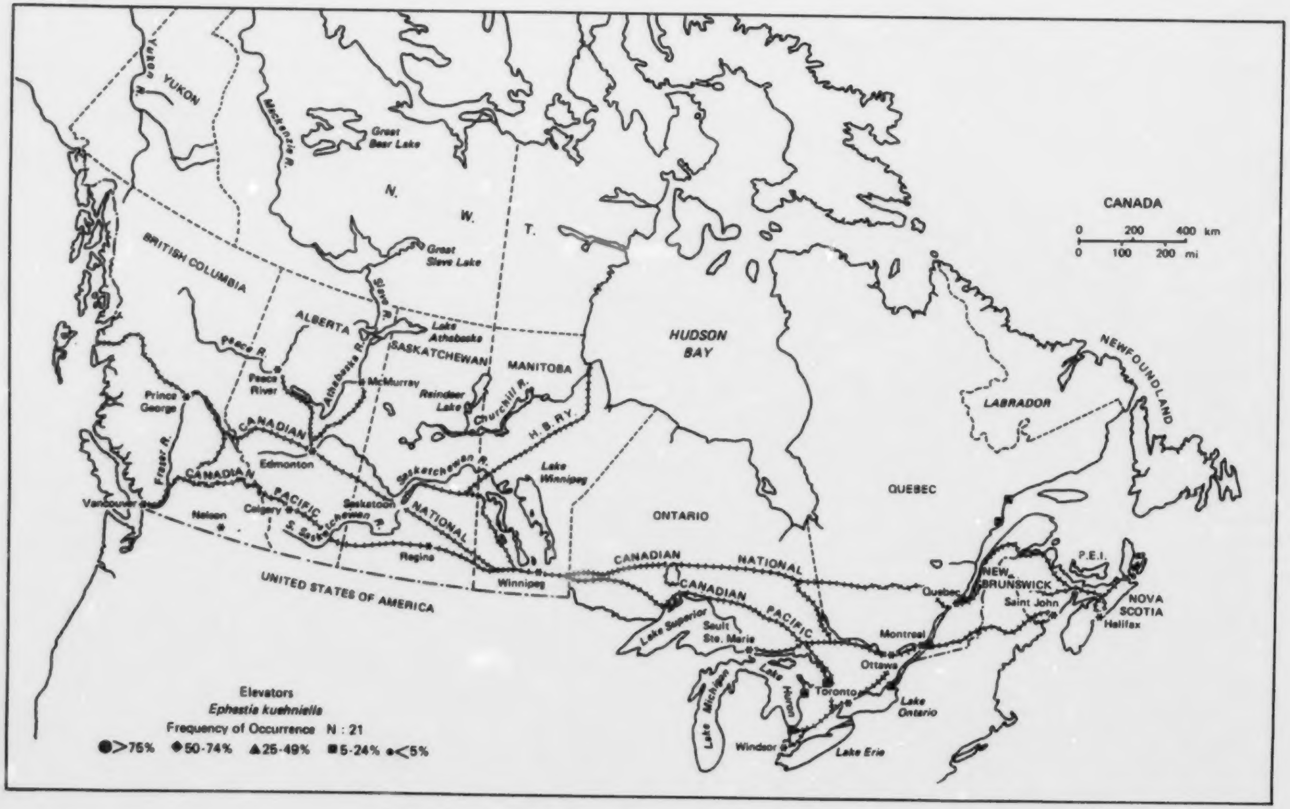
Map 15. Distribution of *Attagenus* spp. in elevators.



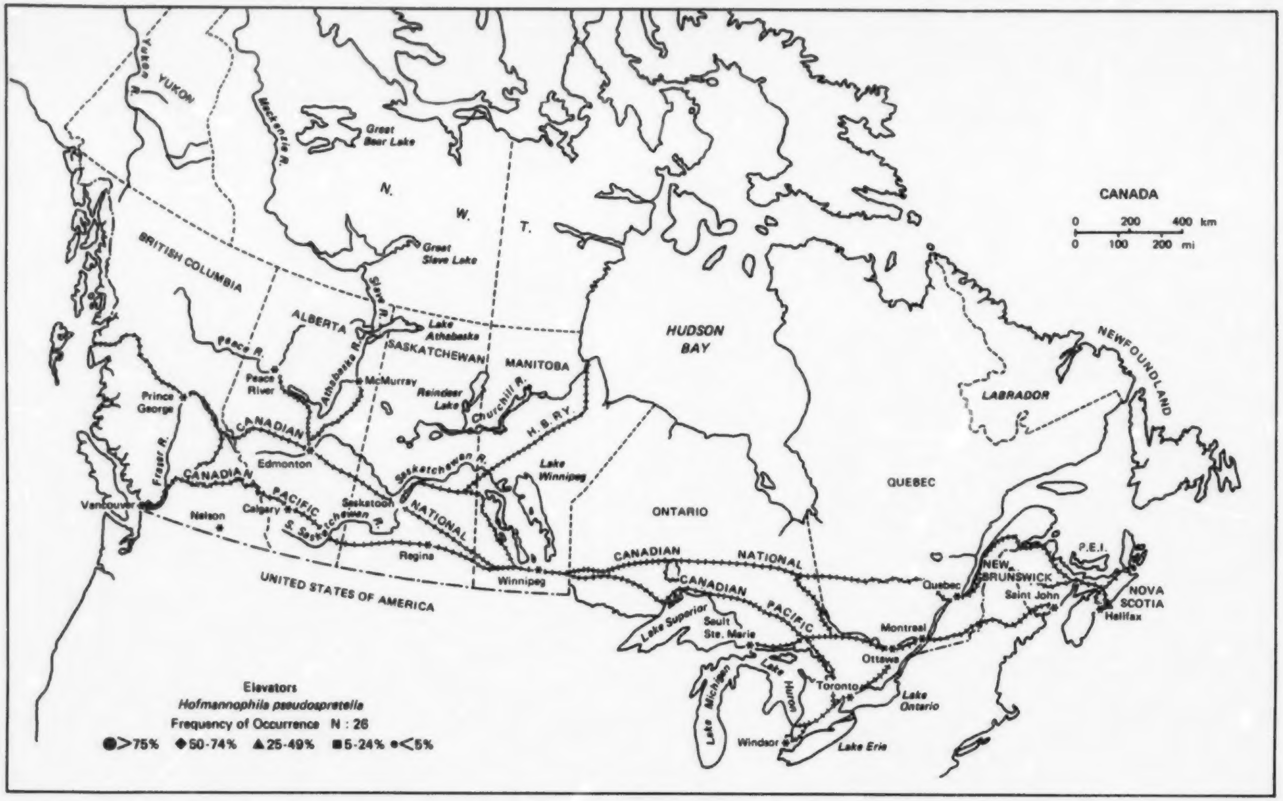
Map 16. Distribution of *Cryptolestes ferrugineus* in elevators.



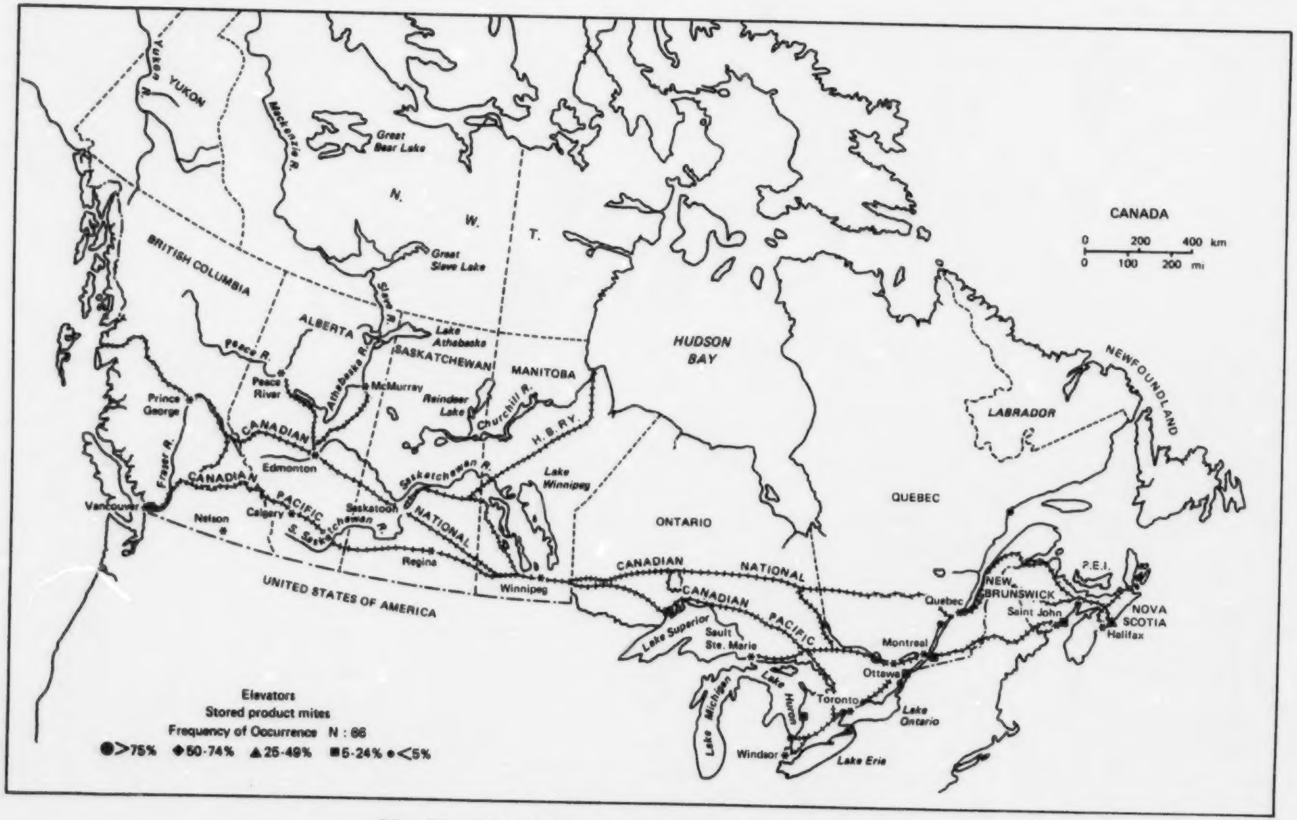
Map 17. Distribution of *Cryptolestes pusillus* in elevators.



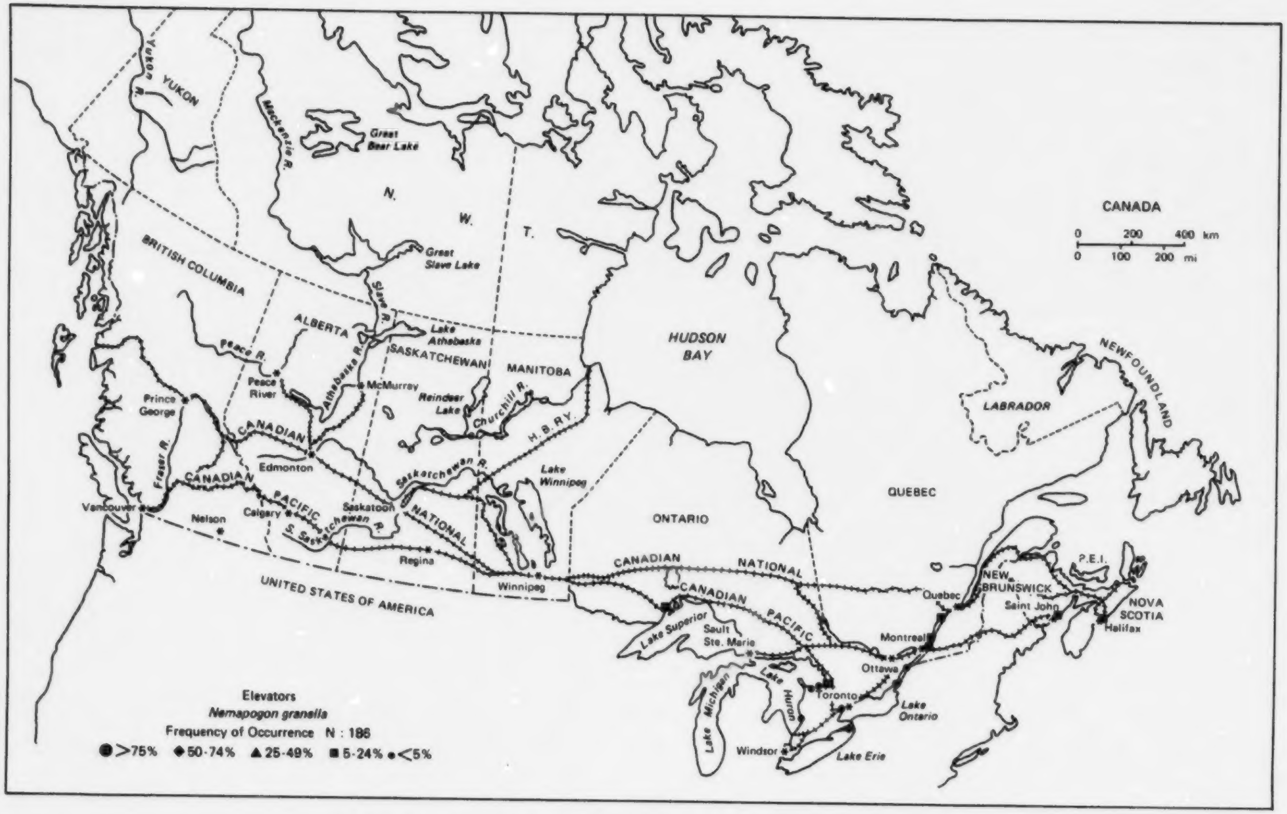
Map 18. Distribution of *Ephestia kuehniella* in elevators.



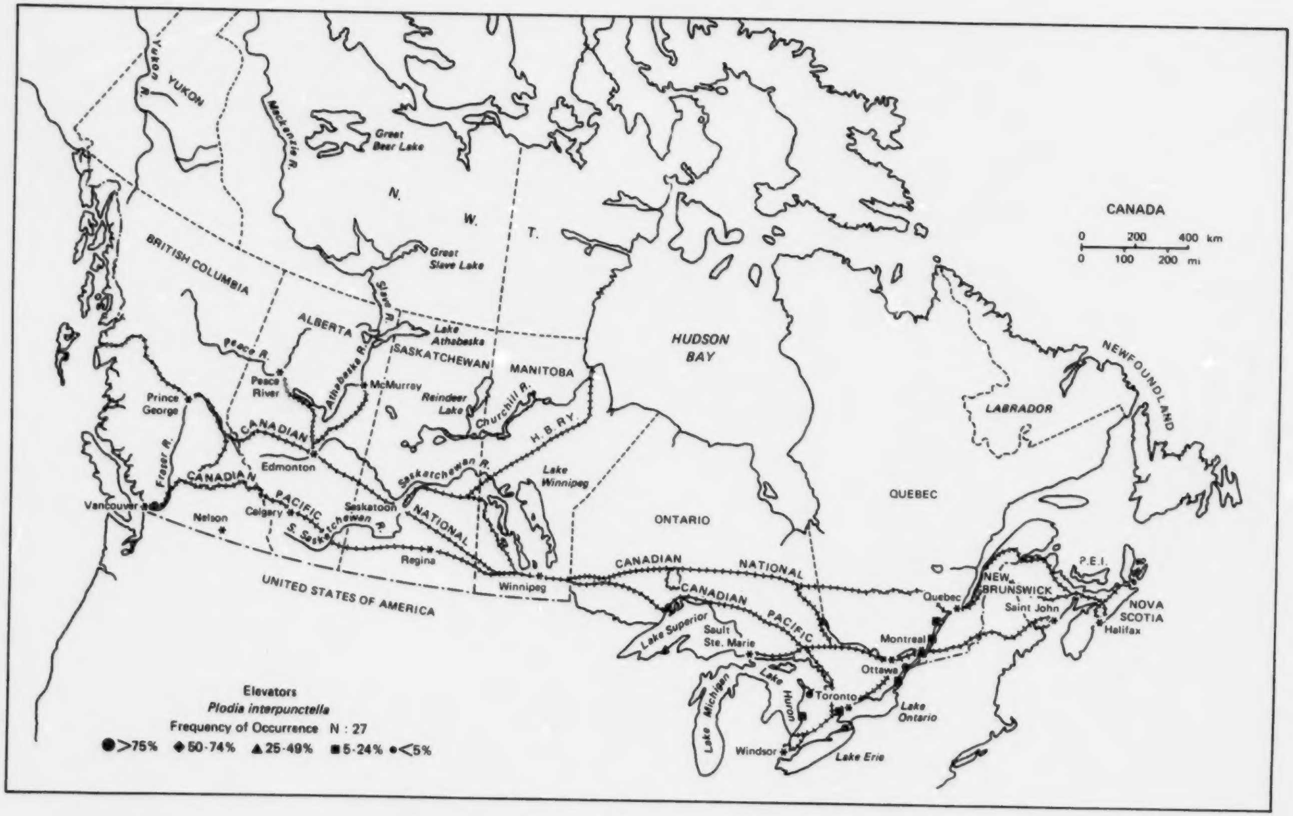
Map 19. Distribution of *Hofmannophila pseudospretella* in elevators.



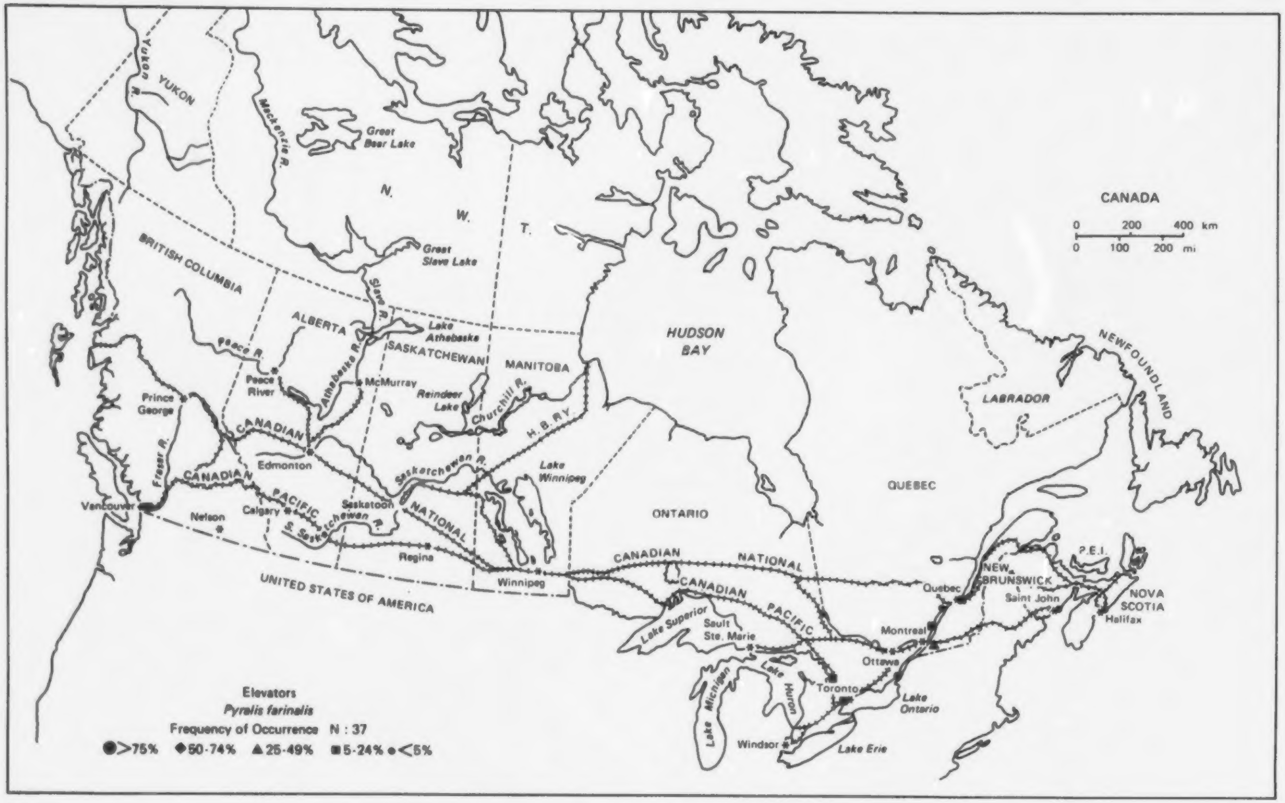
Map 20. Distribution of stored-product mites in elevators.



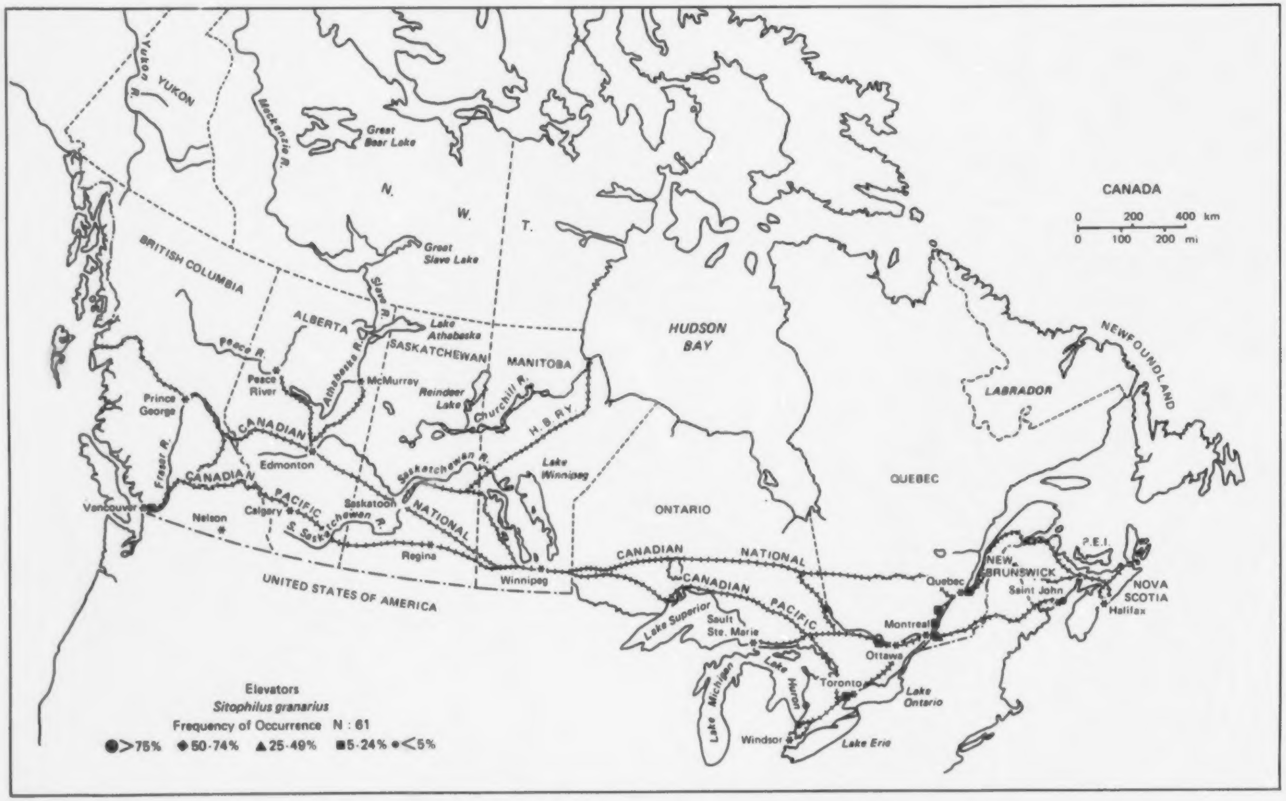
Map 21. Distribution of *Nemapogon granella* in elevators.



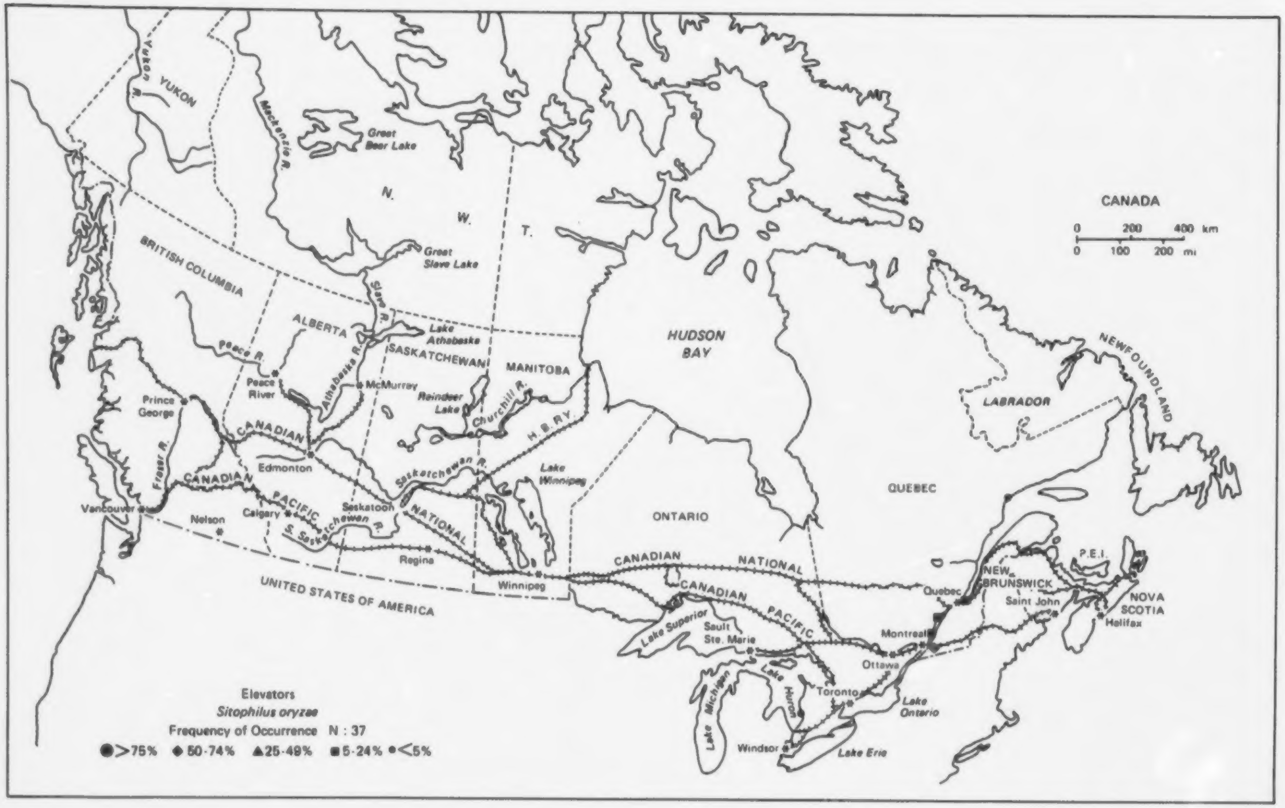
Map 22. Distribution of *Plodia interpunctella* in elevators.



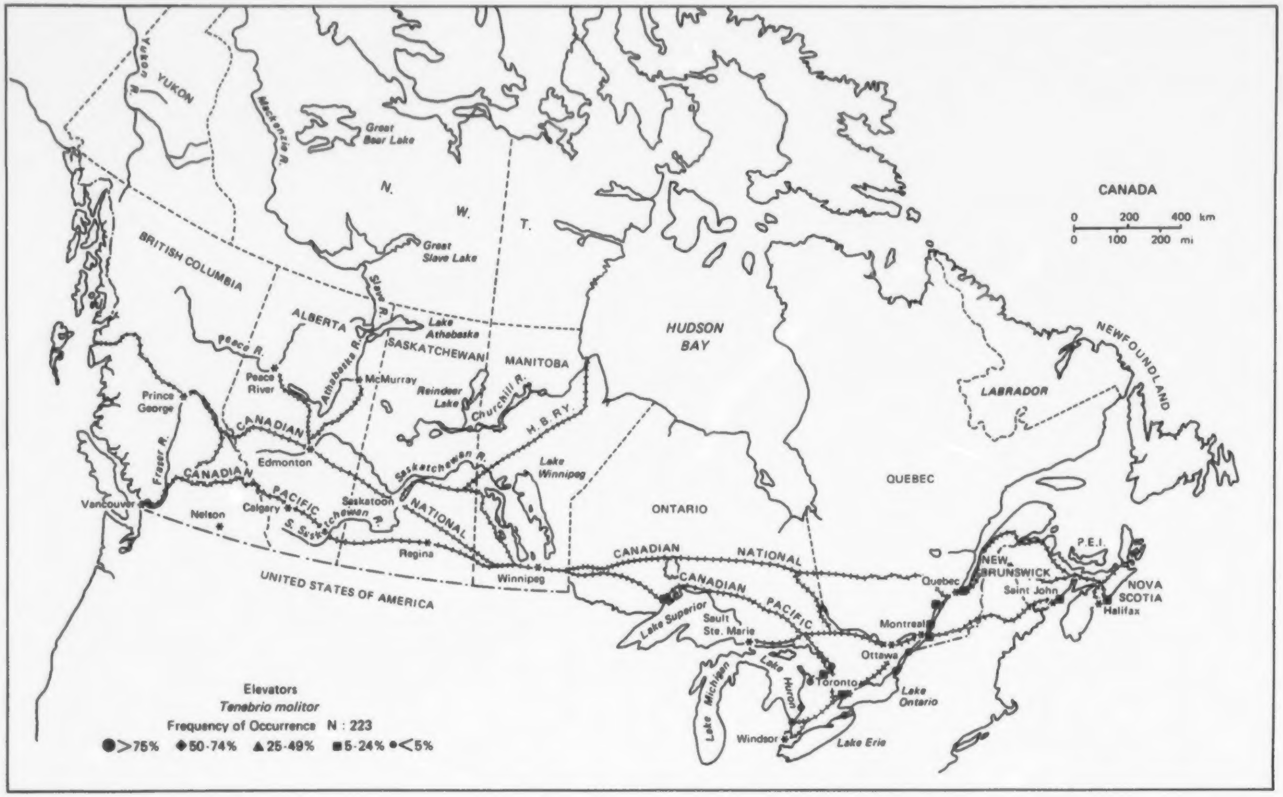
Map 23. Distribution of *Pyralis farinalis* in elevators.



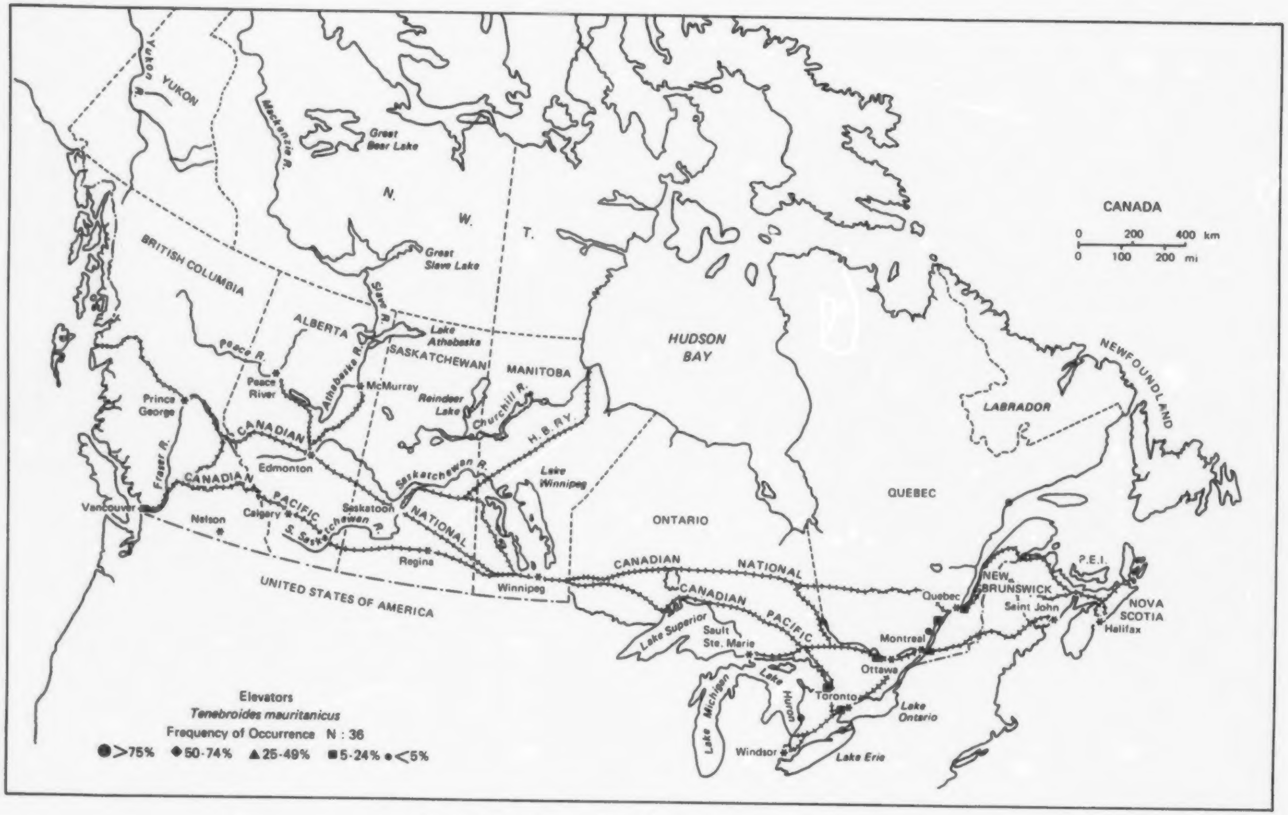
Map 24. Distribution of *Sitophilus granarius* in elevators.



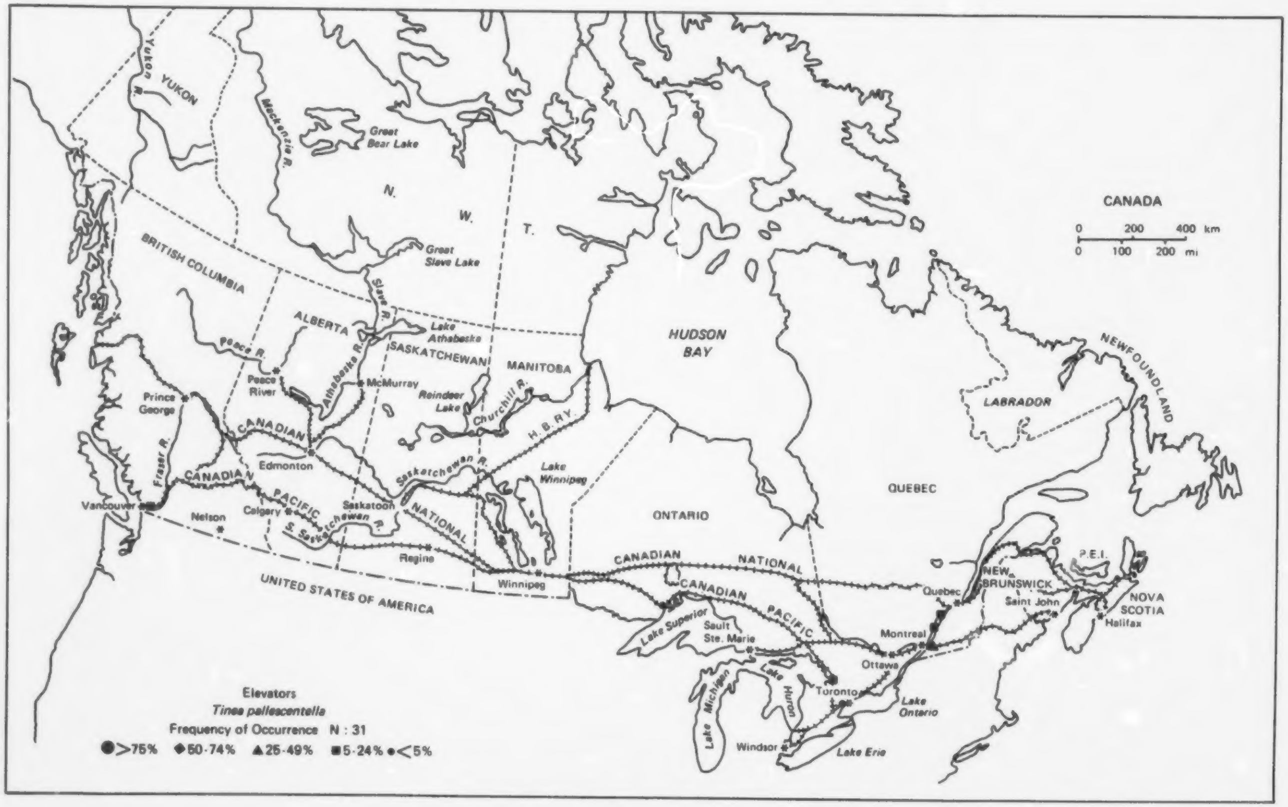
Map 25. Distribution of *Sitophilus oryzae* in elevators.



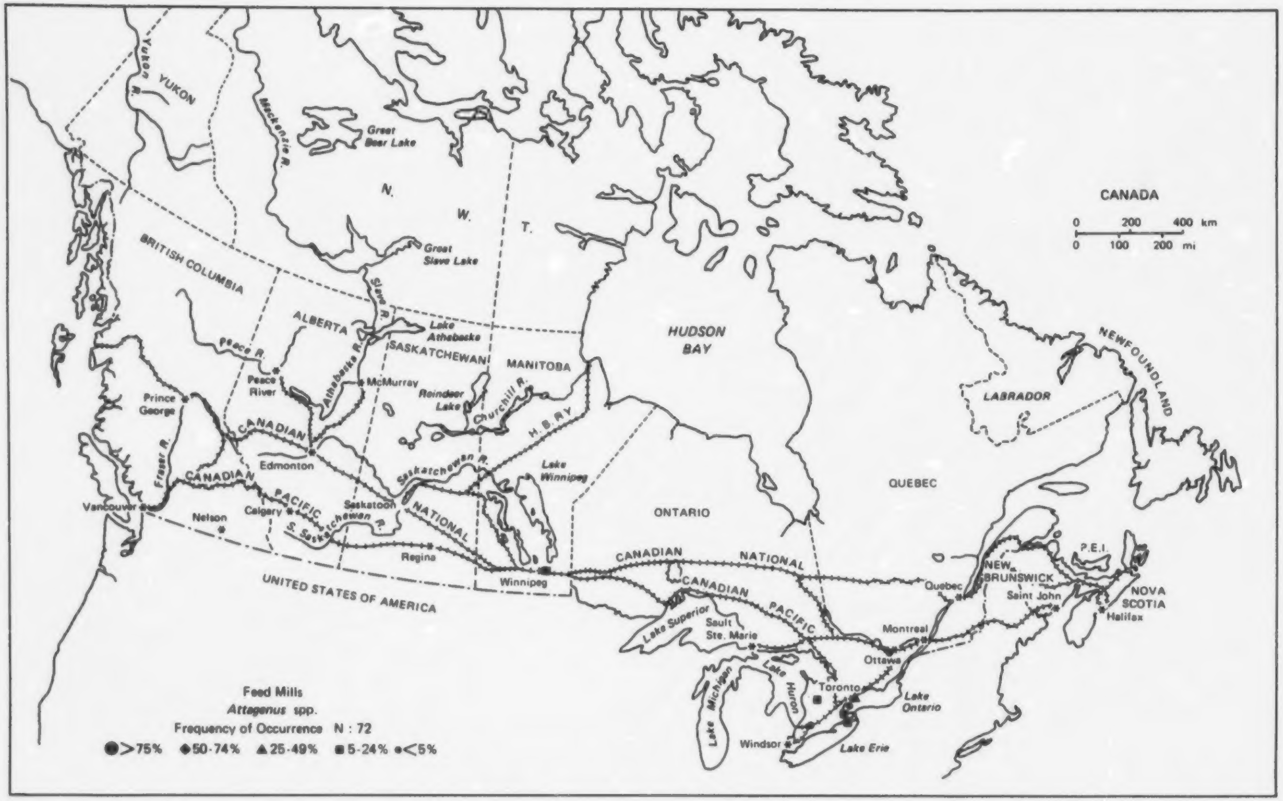
Map 26. Distribution of *Tenebrio molitor* in elevators.



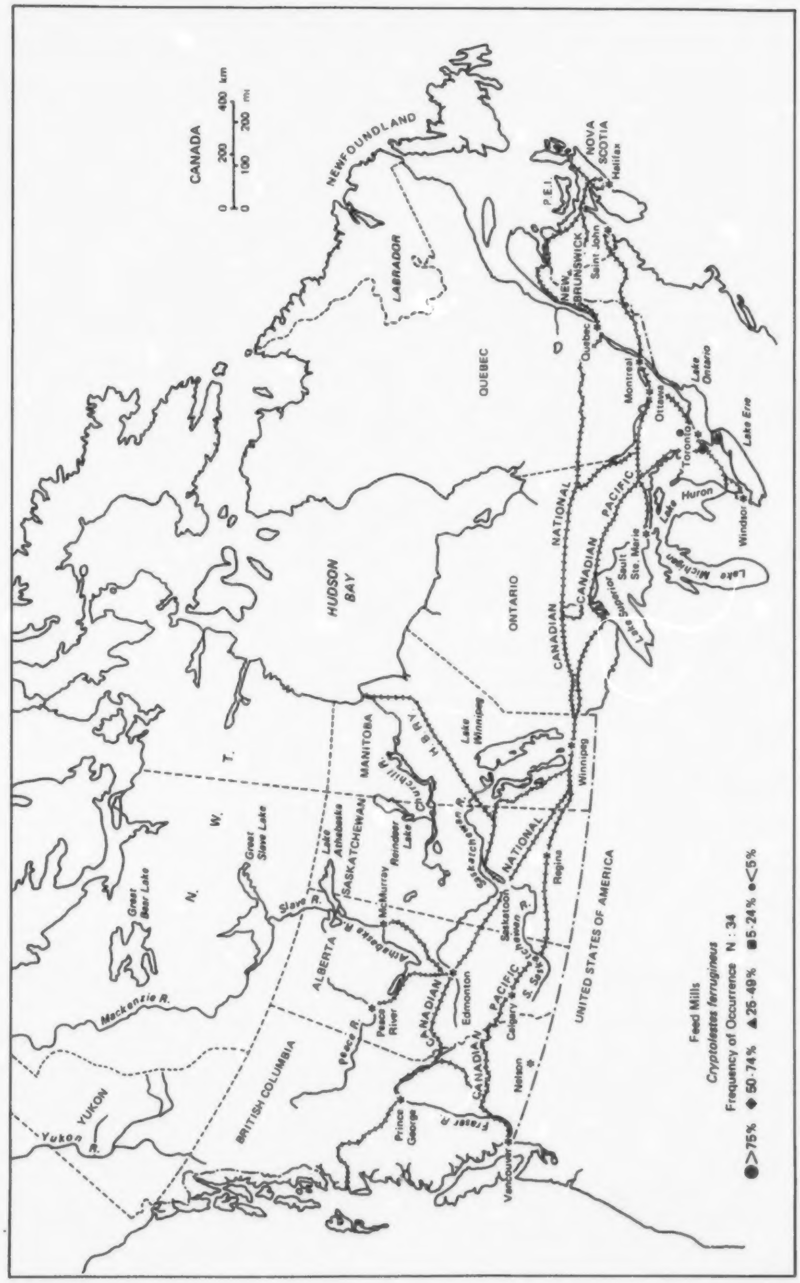
Map 27. Distribution of *Tenebroides mauritanicus* in elevators.



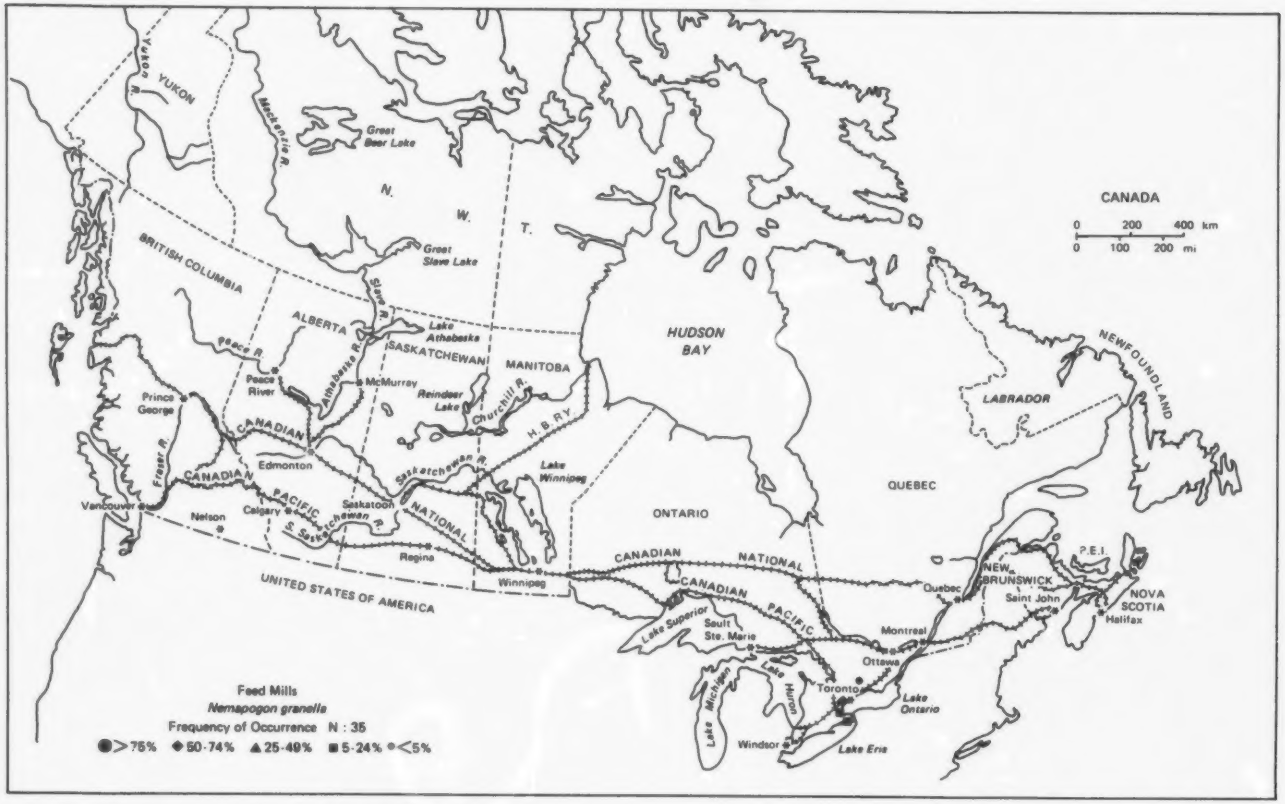
Map 28. Distribution of *Tinea pallescentella* in elevators.



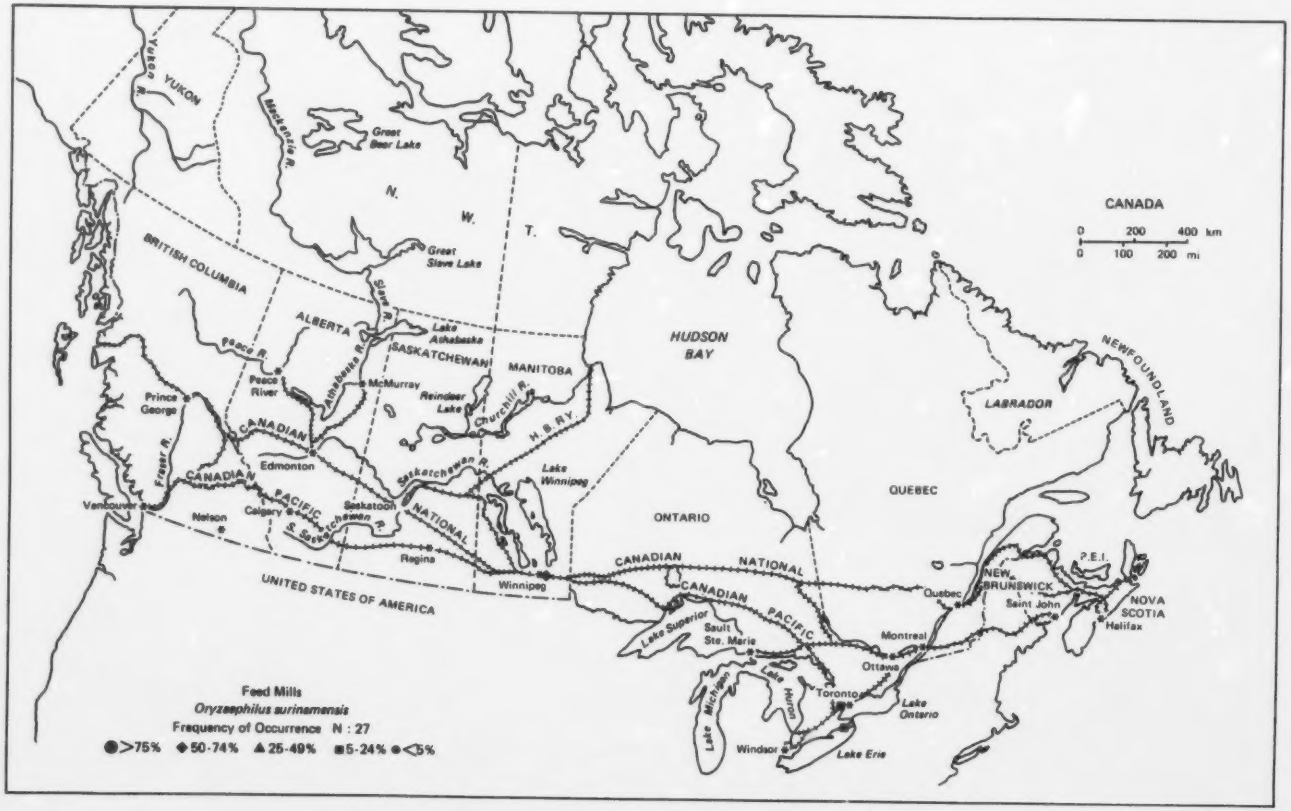
Map 29. Distribution of *Attagenus* spp. in feed mills.



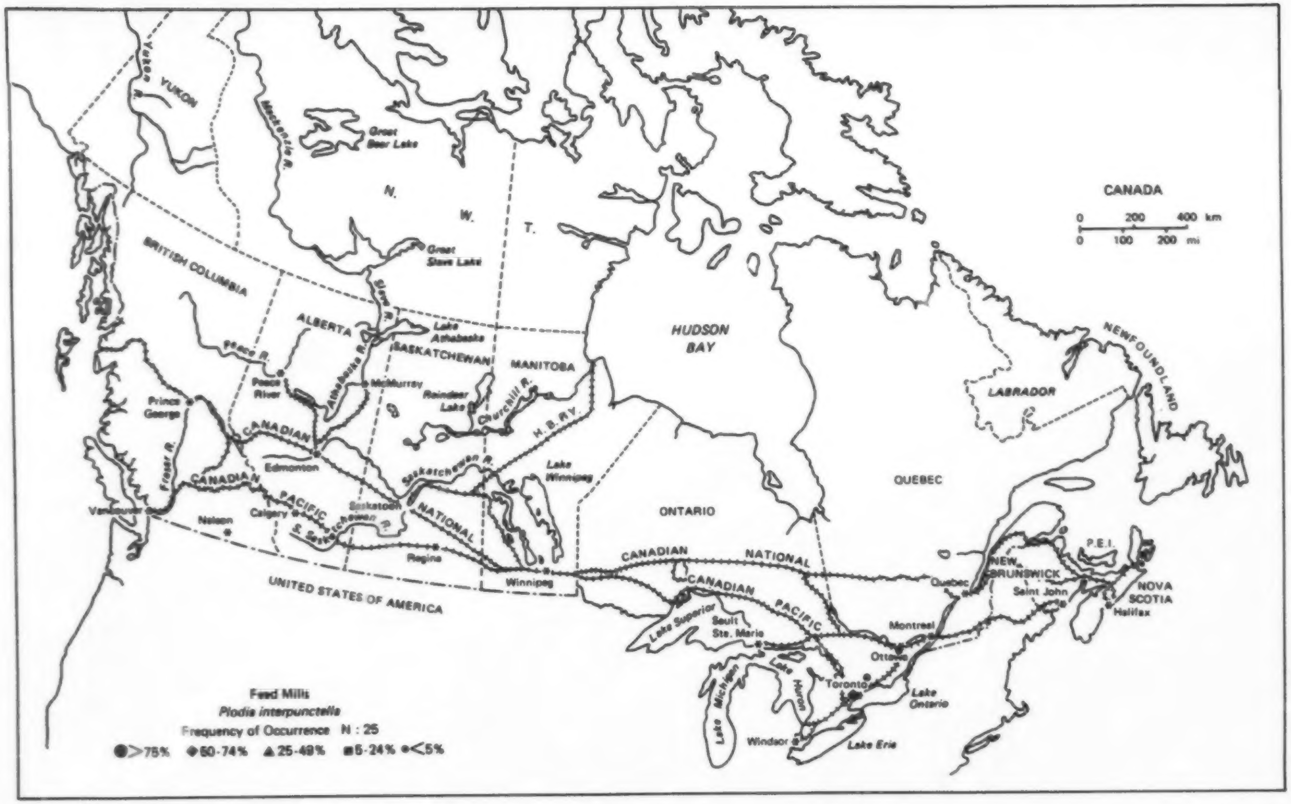
Map 30. Distribution of *Cryptolestes ferrugineus* in feed mills.



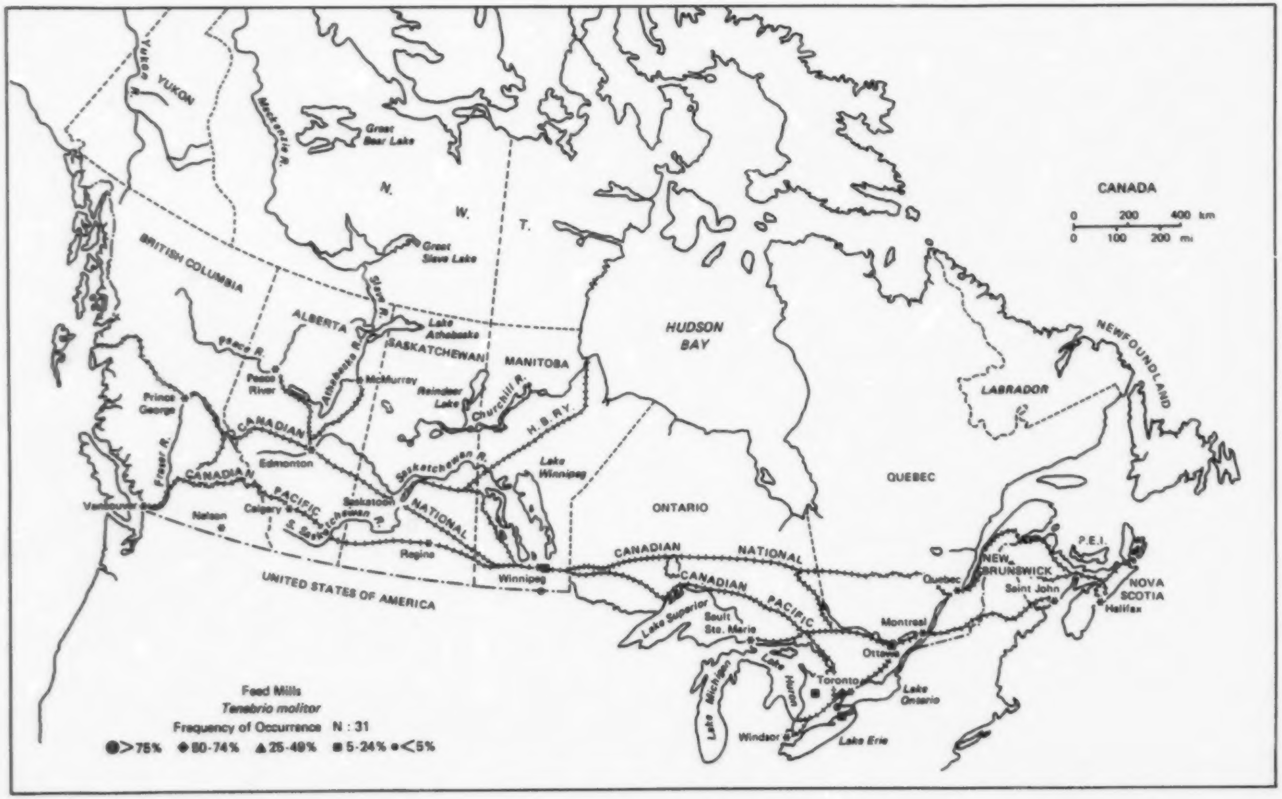
Map 31. Distribution of *Nemapogon granella* in feed mills.



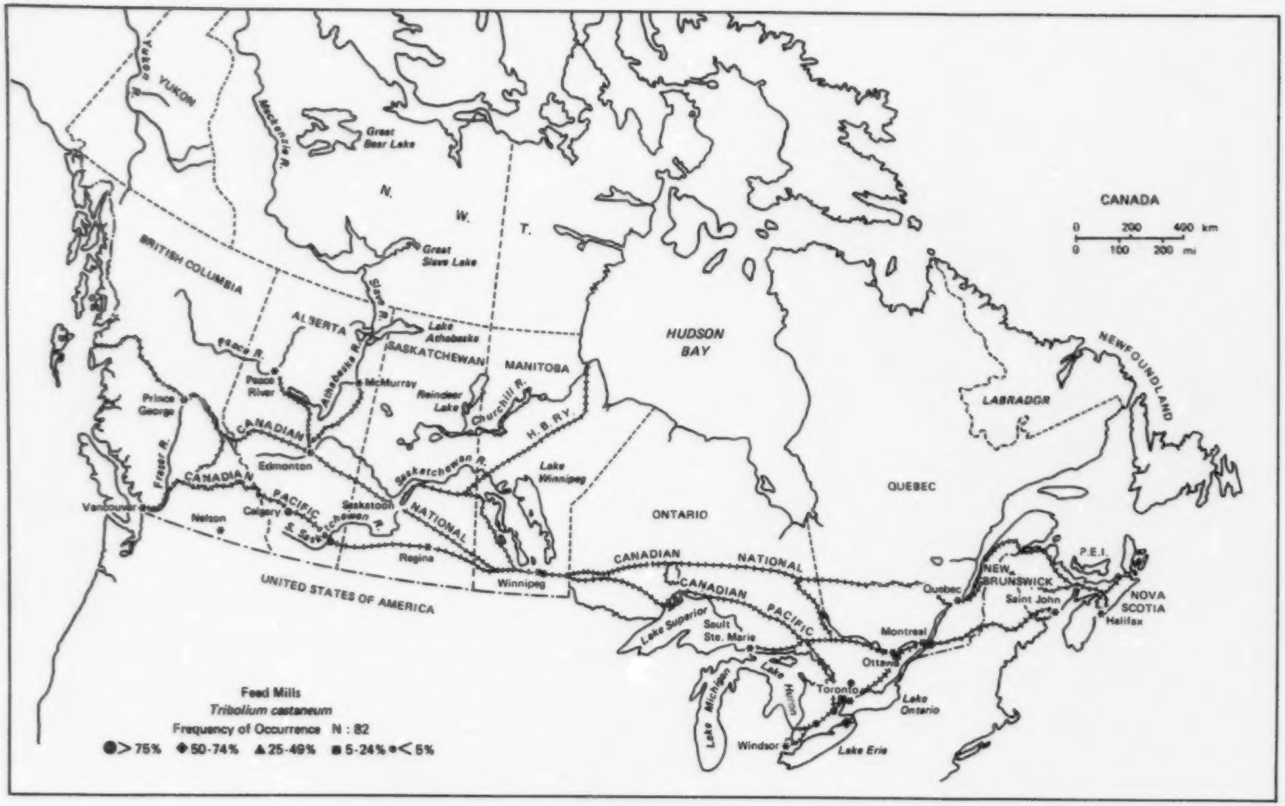
Map 32. Distribution of *Oryzaephilus surinamensis* in feed mills.



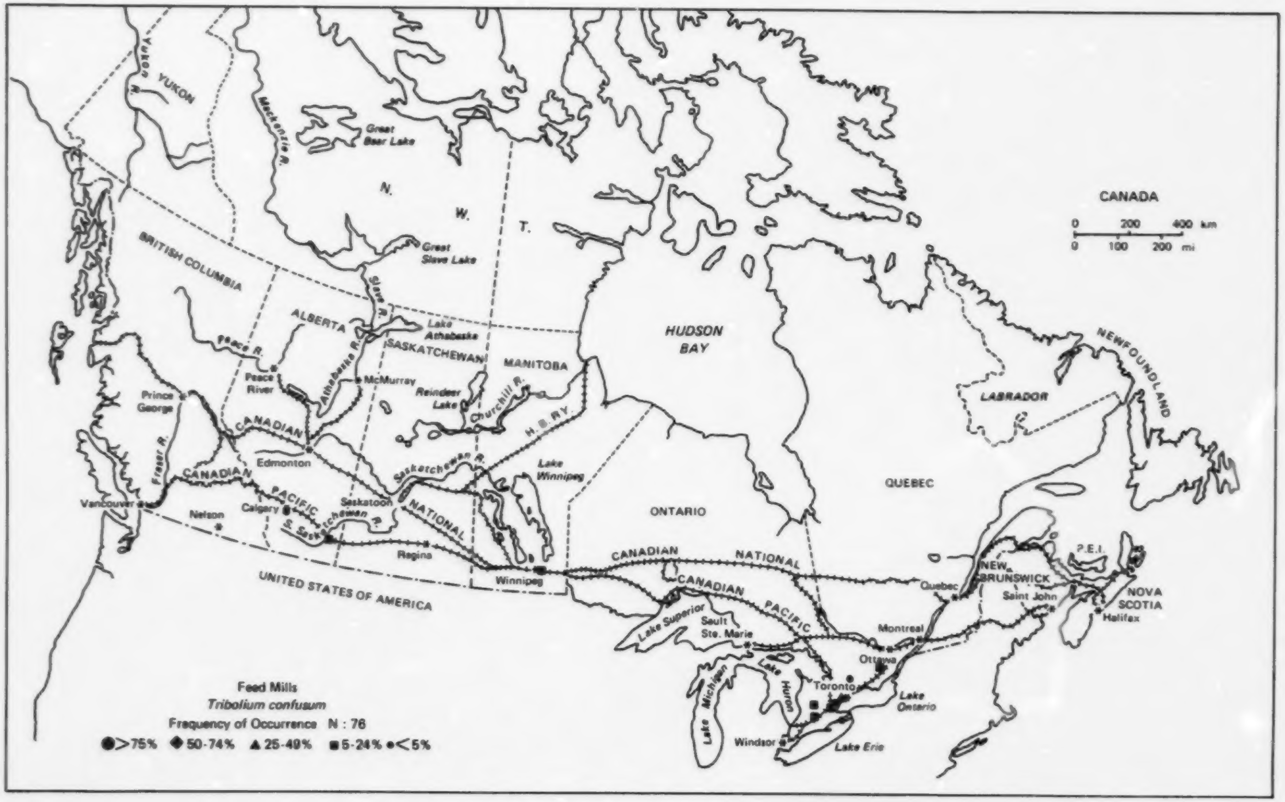
Map 33. Distribution of *Plodia interpunctella* in feed mills.



Map 34. Distribution of *Tenebrio molitor* in feed mills.



Map 35. Distribution of *Tribolium castaneum* in feed mills.



Map 36. Distribution of *Tribolium confusum* in feed mills.

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CONVERSION FACTORS

Metric units	Approximate conversion factors	Results in:
LINEAR		
millimetre (mm)	x 0.04	inch
centimetre (cm)	x 0.39	inch
metre (m)	x 3.28	feet
kilometre (km)	x 0.62	mile
AREA		
square centimetre (cm^2)	x 0.15	square inch
square metre (m^2)	x 1.2	square yard
square kilometre (km^2)	x 0.39	square mile
hectare (ha)	x 2.5	acres
VOLUME		
cubic centimetre (cm^3)	x 0.06	cubic inch
cubic metre (m^3)	x 35.31	cubic feet
	x 1.31	cubic yard
CAPACITY		
litre (L)	x 0.035	cubic feet
hectolitre (hL)	x 22	gallons
	x 2.5	bushels
WEIGHT		
gram (g)	x 0.04	oz avdp
kilogram (kg)	x 2.2	lb avdp
tonne (t)	x 1.1	short ton
AGRICULTURAL		
litres per hectare (L/ha)	x 0.089	gallons per acre
	x 0.357	quarts per acre
	x 0.71	pints per acre
millilitres per hectare (mL/ha)	x 0.014	fl. oz per acre
tonnes per hectare (t/ha)	x 0.45	tons per acre
kilograms per hectare (kg/ha)	x 0.89	lb per acre
grams per hectare (g/ha)	x 0.014	oz avdp per acre
plants per hectare (plants/ha)	x 0.405	plants per acre